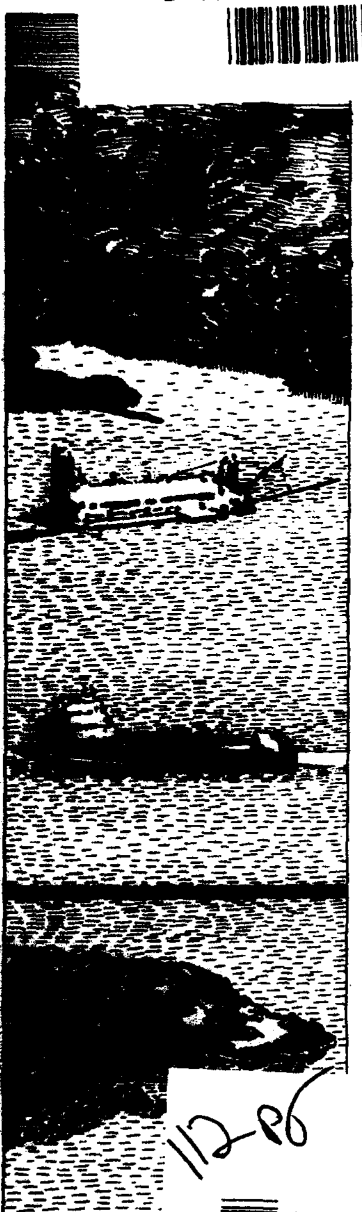
Best
Available
Copy

US Army Corps of Engineers



AD-A280 413

DREDGING RESEARCH PROGRAM

CONTRACT REPORT DRP-94-1

HYDRAULICALLY TRANSPORTED CLAY BALLS

by

Stephen D. Richter, Dov Leshchinsky

Dov Leshchinsky Associates
33 The Horseshoe
Covered Bridge Farms
Newark, Delaware 19711

Final Report

April 1994

Approved For Public Release; Distribution Is Unlimited

112-86

Prepared for DEPARTMENT OF THE ARMY
U. S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by U. S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

Under Work Unit 32471

The Dredging Research Program (DRP) is a seven-year program of the U.S. Army Corps of Engineers. DRP research is managed in these five technical areas:

Area 1 - Analysis of Dredged Material Placed in Open Water
Area 2 - Material Properties Related to Navigation and Dredging
Area 3 - Dredge Plant Equipment and Systems Processes
Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems
Area 5 - Management of Dredging Projects

US Army Corps
of Engineers
Waterways Experiment
Station

Dredging Research Program Report Summary

Hydraulically Transported Clay Balls (CR DRP-94-1)

ISSUE: Predicting the behavior of dredged clay lumps is important in estimating the difficulties associated with the transporting phase of the dredging process. Existing engineering soil descriptors are not oriented toward dredging operations and therefore cannot be used for accurate behavior predictions. Usage of such predictors in practice often leads to disputes among the parties involved in the dredging project.

RESEARCH: The primary objectives of a Dredging Research Program (DRP) work unit entitled "Descriptors for Bottom Sediments to be Dredged" are as follows:

- Identify appropriate geotechnical engineering parameters, develop standard dredged material descriptors based on the parameters, and correlate the parameters with dredging equipment performance.
- Identify techniques suitable for measurement of appropriate geotechnical parameters.

A laboratory study was conducted to establish the empirical relationships between basic clay properties and the degradation rate of clay balls being hydraulically transported. Test variables included clay consistency, degree of compaction of samples relative to their maximum dry density, and type of hydraulic transport.

SUMMARY: Test results showed that plasticity and relative compaction of the soil play a significant role in the rate of degradation of clay balls. Design charts were established to estimate the rate of degradation based on these basic properties. By determining these properties of the sediment at a proposed dredging site, the design charts can be used to predict whether dredged clay lumps will slurrify or whether clay balls will be discharged from a hydraulic dredge discharge pipe. Such information is important in reducing some of the uncertainty commonly assiciated with the planning and execution of a dredging project.

AVAILABILITY OF REPORT: The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, telephone number (601) 634-2355. National Technical Information Service (NTIS) report numbers may be requested from WES Librarians.

To purchase a copy of the report, call NTIS at (703) 487-4780.

[illegible] Geotechnical Laboratory, WES, Principal Investigator for the [illegible]
[illegible] contact Mr. E. Clark McNair, Jr., Manager, DRP, at (601) [illegible]

Dredging Research Program

Contract Report DRP-94-1
April 1994

Hydraulically Transported Clay Balls

by Stephen D. Richter, Dov Leshchinsky
Dov Leshchinsky Associates
33 The Horseshoe
Covered Bridge Farms
Newark, DE 19711

Accesion For	
NTIS CRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

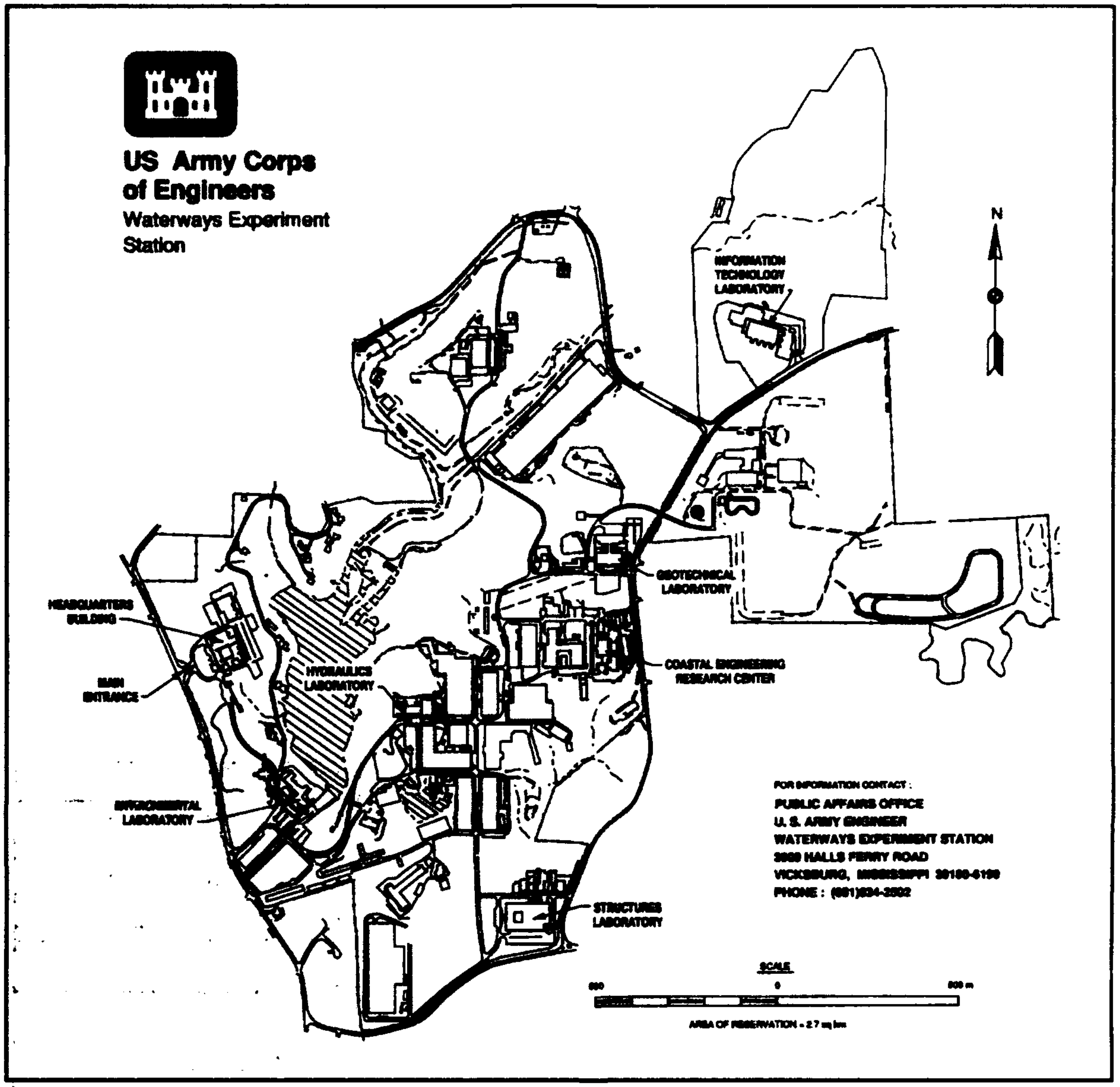
Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

Under Work Unit 32471



Waterways Experiment Station Cataloging-in-Publication Data

Richter, Stephen D.
Hydraulically transported clay balls / by Stephen D. Richter, Dov Leshchinsky ; prepared for Department of the Army, U.S. Army Corps of Engineers ; monitored by U.S. Army Engineer Waterways Experiment Station.
110 p. : ill. ; 28 cm. — (Contract report ; DRP-94-1)
Includes bibliographical references.
1. Ball clay. 2. Clay. 3. Dredging. 4. Soil degradation. I. Leshchinsky, Dov. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Dredging Research Program. V. Title. VI. Series: Contract report (U.S. Army Engineer Waterways Experiment Station) ; DRP-94-1.
TA7 W34c no.DRP-94-1

Contents

List of Figures

Preface

This report was prepared under Contract No. DACW39-91-C-2471, dated 31 May 1991, for the U.S. Army Engineer Waterways Experiment Station (WES) under the Dredging Research Program (DRP) Technical Area 2, Work Unit 32471, Descriptors for Bottom Sediments to be Dredged. The DRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Technical Monitor for Technical Area 2 was Mr. Barry W. Holliday; Chief Technical Monitor was Mr. Robert H. Campbell.

This report was written by Drs. Stephen D. Richter and Dov Leshchinsky, Leshchinsky Associates, under the supervision of Dr. Jack Fowler, Principal Investigator, Soil Mechanics Branch (SMB), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), WES. Mr. W. Milton Myers was Chief, SMB, Dr. Don Banks was Chief, S&RMD, and Dr. W. F. Marcuson III was Director, GL. Dr. Banks was also Manager for DRP Technical Area 2. Mr. E. Clark McNair, Jr., and Dr. Lyndell Z . Hales were Manager and Assistant Manager of the DRP, Coastal Engineering Research Center (CERC). Dr. James R. Houston was Director, CERC, and Mr. Charles C. Calhoun, Jr., was Assistant Director, CERC, which oversees the DRP.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K Howard, EN.

For further information concerning this report, contact
Dr. Jack Fowler (601) 634-2703, or Mr. E. Clark McNair, Jr.,
(601) 634-2070.

Summary

Behavior of dredged clay lumps varies widely depending upon their geotechnical characteristics. Predicting the behavior of clay lumps is important in estimating the difficulties associated with the transporting phase of the dredging process. Existing engineering soil descriptors are not oriented towards dredging operations and therefore cannot be used for accurate behavior predictions. Usage of these predictors in practice often leads to disputes between the parties involved in the dredging project.

This work presents empirical relationships between basic clay properties and the degradation rate of clay balls being hydraulically transported. Various clay consistencies were simulated in the laboratory using different proportions of kaolinite and bentonite in the mixture. These clays were then statically compacted to different degrees of density relative to their maximum standard Proctor dry density. To simulate the hydraulic transport effects, samples were subjected to two types of tests. In the first one, clay samples were clamped and lowered underwater and were spun for different times and velocities. The remaining intact portions of the samples were then dried and weighed to determine the effect of the relative movement of water against the clay. In the second test, clay samples were placed in a drum, partially submerged in water. The drum was rotated for different times and various velocities. Intact portions of samples were then removed from the drum, dried, and weighed to determine the effect of agitation.

The results of the testing program showed that plasticity and relative compaction of the soil play a significant role in the rate of degradation of clay balls. Clays that exhibit a plasticity index greater than 25 will form clay balls. The rate of degradation will depend on the density of the clay. Through extensive testing, design charts have been established to estimate the rate of degradation based on these basic properties. By determining these properties of an in situ soil, one can then predict whether the dredged clay lumps will slurrify or whether clay balls will be discharged from a hydraulic dredge discharge pipe. The results appear to be important to the dredging industry, as they reduce some of the uncertainty commonly associated with the planning and execution of a dredging project.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	2.54	centimeters
pounds (force)	4.448222	newtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
tons per square foot	47.88026	pascals

1 Introduction

The behavior of clay lumps cut in the dredging process varies widely depending upon the geotechnical characteristics of the soil. Friable clays slurrify rapidly when cut and transported hydraulically (Figure 1). This facilitates the dredging process but necessitates containment of the spoils. Other clays will not break down, but rather deform plastically into a ball shape (Figure 2). This phenomenon may or may not be beneficial, depending on the application. For example, if a dike is to be constructed using the hydraulic fill, then clay balling is desirable since it makes the construction feasible (Figure 3). However, clay lumps slow down the transport process and, in extreme cases, may clog the dredge pipeline. Predicting behavior of dredged clay lumps is thus necessary to estimate the dredging difficulty and its associated cost, and to plan the best method for handling the dredged material.

At the present time, there is no standard system for identifying, describing, and classifying soils to be dredged. The purpose of this study is to quantify empirically the relationships between the basic clay properties and the degradation rate of clay lumps in an environment that simulates hydraulic transport conditions. The clay properties that control friability can then be determined in situ for the soil to be dredged. Using these properties, the empirical relationships established in this study, and the anticipated exposure time and conditions in a dredge pipeline, predictions regarding the lump degradation, selection of dredging equipment, and cost estimates can be made in a rational manner. However, since this study was carried out in a simulated laboratory environment, a simple and straightforward field verification is necessary. The verification may lead to further refinement of the empirical relationships established in this study.

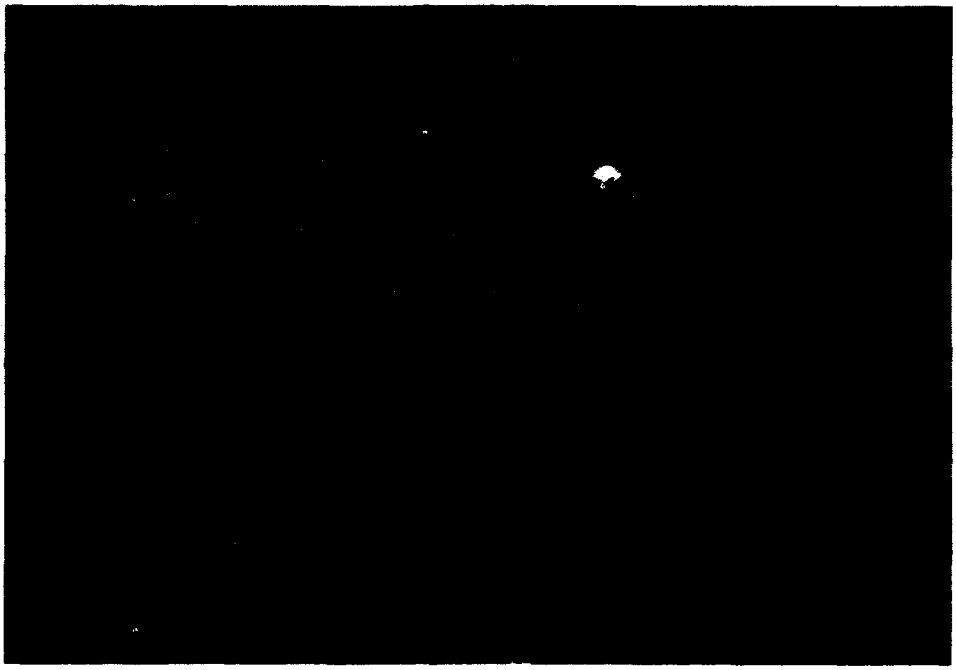
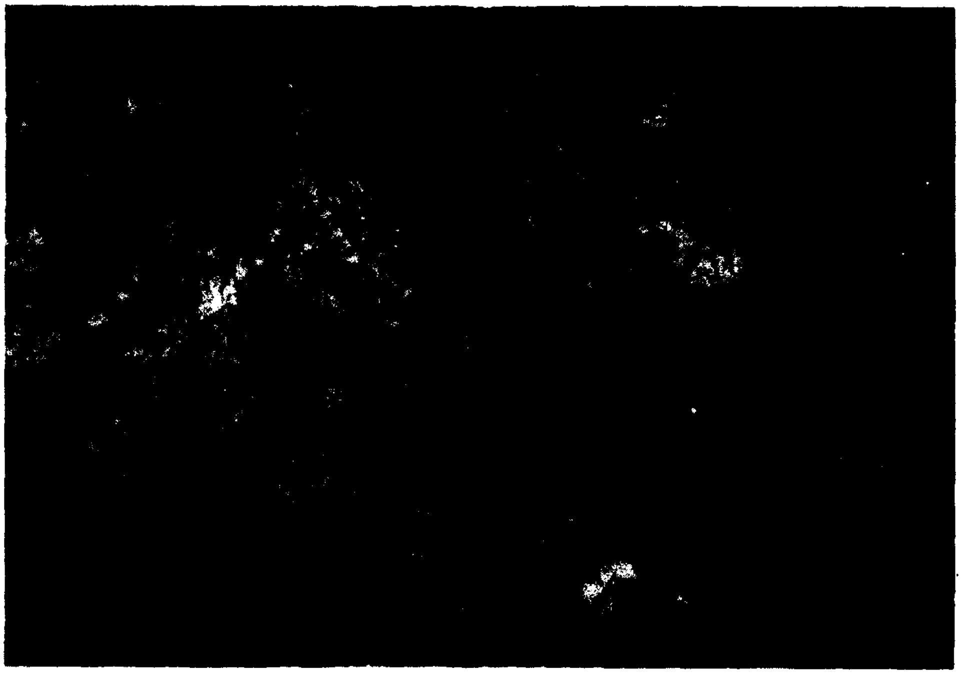
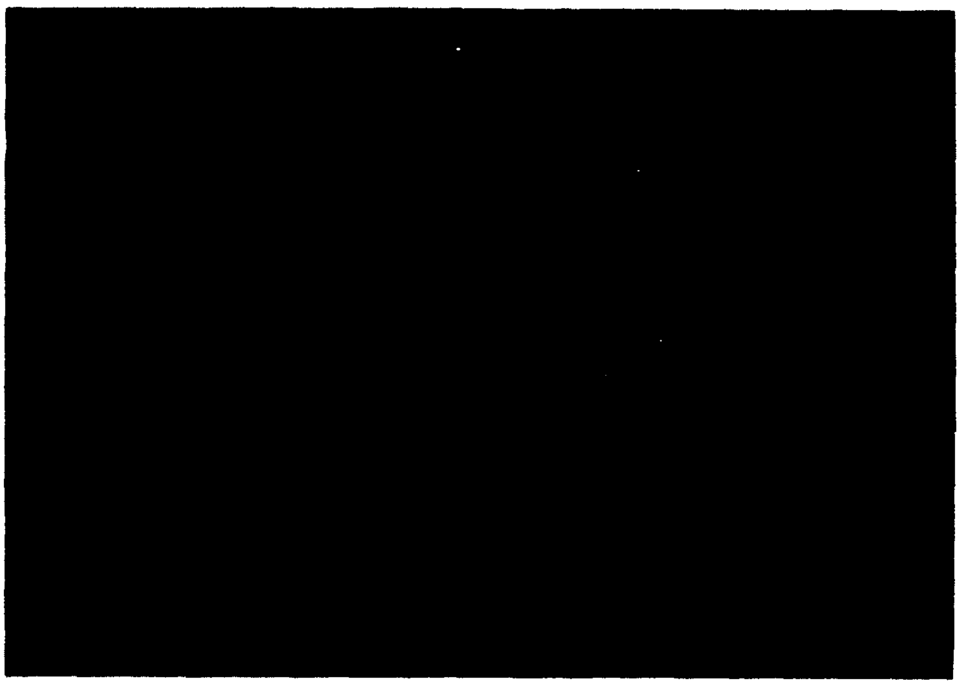


Figure 1. Disposal site: slurrified clay



(a)



(b)

Figure 2. Clay balls at disposal site: (a) wet, and (b) dry

Figure 3. Clay balls used to construct a steep dike

2 Background

General

Dredging is most often performed to construct and maintain harbors and waterways. Dredging is also used extensively in mining of materials such as sand, coal, and even gold and diamonds. Hydraulic fill in a dredging operation is an efficient process by which solids cut by the dredge are transported from the excavation site to the disposal area using water flow as a carrier. The ease within which the solids are transported depends, to a large extent, on their geotechnical properties.

A dredge is a floating machine that removes underwater bottom material and transports it in a closed conduit to a disposal area. Many different types of dredges have been developed over the years to facilitate the dredging process. Today's dredges are large and powerful machines which, under the proper conditions, can move large quantities of material very efficiently. The most common types of dredges used are the plain suction, hopper, dustpan, and cutterhead. The mechanisms by which each of these operates are discussed in detail by Turner (1984). This study is concerned with the dredging of clays for which the cutterhead dredge is almost exclusively used. Cutterhead dredges are classified by their intake suction pipe diameter. As such, cutterhead dredge intakes range in size from 8 in. to 42 in.

Annual dredging volume in the United States performed for navigation purposes averages about 500 million cu yd a year. Of this amount about 80 percent is performed by cutterhead dredges (Mohr 1980). Most dredging activities in the United States are managed by the U.S. Army Corps of Engineers who have responsibility to maintain navigable waterways. The Corps plans dredging projects and, typically, contracts the necessary work to private dredging companies. The dredging contractor is usually paid for his work based on the volume of in situ material removed.

Significance of dredging

In the United States there is currently a large interest in improving navigational capabilities. Most U.S. ports have a required depth of 40 ft below mean

low water (National Research Council Marine Board 1985). These depths were established decades ago and are indirectly based on the draft of ships that can pass through the Panama Canal. Today's fully loaded large ships such as supertankers, however, require drafts up to 90 ft. Since large ships offer lower-cost transportation, they are increasingly being used and, therefore, require deeper ports and channels. In 1985 the United States imported 22 percent of all goods consumed and exported such bulk material as coal, grain, and timber (National Research Council Marine Board 1985). Most large ships carrying these goods in and out of U.S. ports have two options. They must go through the process of lightening and topping off at sea before entering U.S. waterways or operate at a fraction of their fully loaded capacities. Either option adds a cost to the goods they carry. Dredging should enable larger ships easy access to ports and, therefore, can be seen as a way to ultimately reduce cost.

Dredged type of soils

Dredging work falls into two major categories: maintenance and new construction. Maintenance dredging involves removal of sediments drifting into waterways to keep facilities in their original condition. This type of work is required due to inland erosion and sediment deposited by tides. The geotechnical properties of material dredged for maintenance purposes usually allows for easy dredging because of their low unit weight. Construction dredging involves creating new navigational facilities or making improvements to those that already exist. New construction dredging normally involves moving dense sand, clay, or even rock.

Dredging costs can run from pennies to several dollars per cubic yard. This wide range of costs is due mainly to the variety of soils and geotechnical conditions involved. The soils to be dredged can be classified into three groups: cohesive soils (clay and silty clays), cohesionless soils (sand, silty sand, and gravel), and rock (Verbeek 1984). In 1978 the following percentage breakdown by types of material were dredged in the United States (National Research Council Marine Board 1985):

Sand and Silt	44 percent
Clays	35 percent
Gravel	16 percent
Other	5 percent

The Hydraulic Suction Cutterhead Dredge

Materials that are difficult to cut (e.g., boulders or cobbles) are best removed by mechanical means. Extremely loose soils are best removed by a pure suction dredge, such as a dustpan. Cohesive or dense soils are most efficiently cut and moved by the suction cutterhead method. Because the

scope of this study is limited to clays, the only dredge that will be further discussed is the hydraulic suction cutterhead.

The main components of this dredge are the cutterhead, pump, and pipeline. The cutterhead is a multibladed device which rotates around a shaft. The cutterhead functions by loosening material, cutting, and placing it into a suction intake. Consideration must be taken so that the cutterhead does not dispel the materials it contacts. The cutterhead can vary in size, shape, number of blades, type of cutting edge, and rake angle (Turner 1984). Problems with selecting the proper cutterhead usually do not exist in sand. However, when cohesive material must be cut to a compatible pumping size or to avoid clay ball formation, proper selection of a cutterhead is important.

Pumped fluid transports the dredged material, mainly as a slurry, in the pipeline. Centrifugal pumps are most often used to transport the slurry. The centrifugal pump contains impellers which rotate through the fluid. The fluid is then impelled by centrifugal force into the pump casing where velocity is converted into head. This head causes flow of slurry (or water containing solid lumps) in the pipeline. Friction in the pump and pipeline system reduces total head along the pipeline and, as it declines toward barometric pressure, flow is reduced towards zero.

Friction Losses and Clay Balls

Friction losses in a pipeline are greatly dependent on the type and rate of dredged material being hydraulically transported. Figure 4 illustrates three different flow regimes for solids carried in a pipeline. Each of these regimes is associated with friction losses of a different order of magnitude (Turner 1984). The figure shows that transport of material can occur as a homogeneous suspension, a heterogeneous suspension with some soil particles in suspension and some particles rolling over the bottom, or as a moving bed where soil particles are dragged over the bottom. The type of flow occurring in a given dredgeline is a function of several parameters: (1) fluid velocity and turbulence, and (2) particle size, shape, and density. Noncohesive soils move as discrete particles and the fluid velocity is normally maintained so that the material flows as a heterogeneous suspension. Fluid velocity in the pipeline is quite effective in keeping noncohesive particles in suspension and friction losses are then relatively small.

Cohesive soils excavated by the cutterhead move into the pipeline typically as lumps. Similar to the noncohesive soils, cohesive ones are also transported through the pipeline by fluid velocity and turbulence. However, unlike sand, if the lumps are not friable, they will be carried as a moving bed in the bottom of the pipe. Because moving bed flow is less efficient than suspended particle flow, the intake of clay materials must be reduced to keep friction (and adhesion) losses low enough to maintain flow. In fact, if the clay is sticky, it may clod, creating clay balls (i.e., particles may adhere to each other), thus

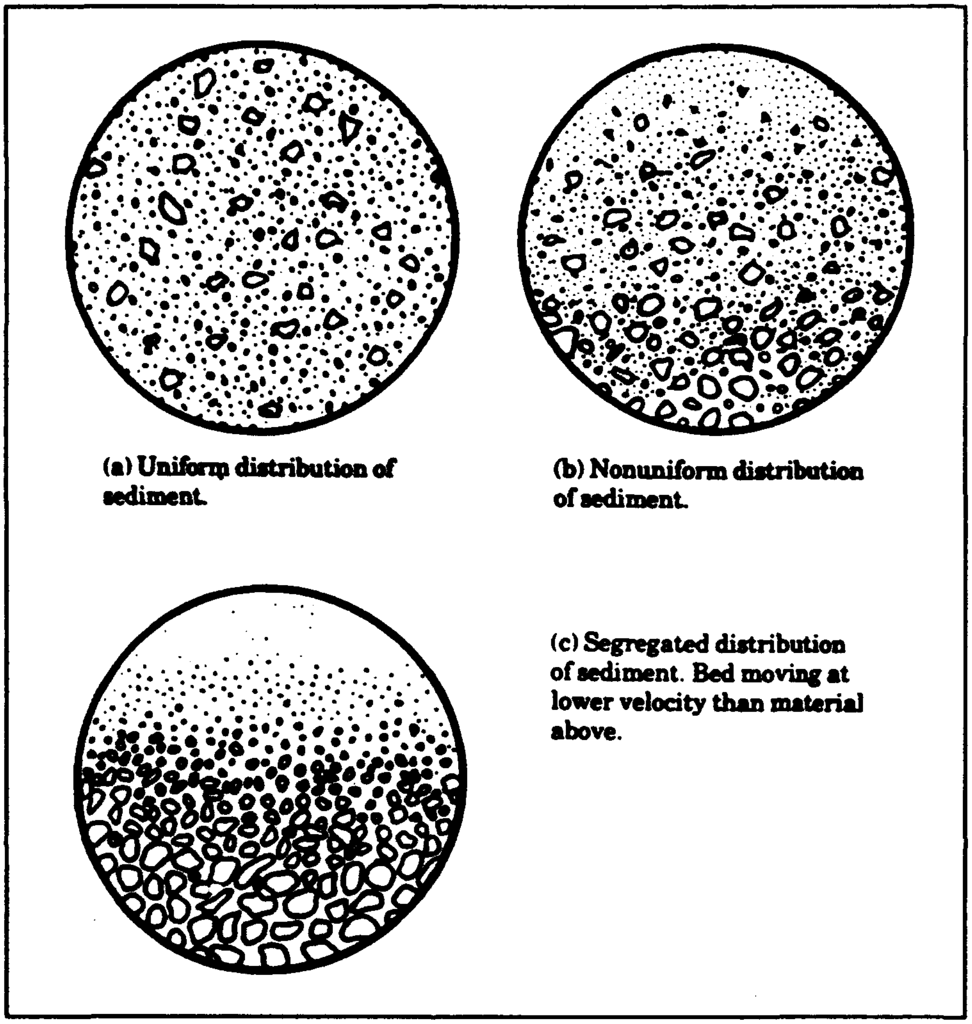


Figure 4. Flow regimes in a pipeline: (a) homogeneous flow, (b) heterogeneous flow, and (c) flow as a moving bed (Turner 1984)

limiting the distance reached by the hydraulic pipeline (Spigolon 1988). Verbeek (1984) and Sorensen (1984) reported that clay balls are likely to form when the liquid limit equals 35 percent to 50 percent or 80 percent to 120 percent, the plastic limit is higher than 20 percent to 30 percent, the density of the soil is higher than 93 to 106 pcf, and the shear strength is greater than 3.6 psi. As a result, clay materials are typically transported at 4 percent to 5 percent by volume in situ material to the total flow in the pipeline (Schnider 1991).[1] Some clays begin to slurrify as they are transported, resulting in a decrease in friction loss, thus allowing a higher percentage of solids. The degree of slurrification is thought to depend on undrained shear strength and the plasticity index (Verhoeven, Jong, and Lubking 1988). The results of this work indicate

[1] Personal interview, 1991, Walter Schnider, American Dredging Company, Inc.

that the plasticity index is indeed a primary factor in lump degradation (or slurrification) where the density (or shear strength) is a secondary one.

Improvements Needed in Material Classification

There is a clear need in the dredging industry for descriptors to classify materials. Presently, no unified method exists for testing and relating information about material to be dredged. Investigations done prior to dredging projects are not systematic and the subsequent reports do not describe in a meaningful way the material's relevant properties. This is a critical problem since the financial success of most dredging projects depends on an accurate prior estimate of cutting and pumping efficiency. The efficiency, in turn, is affected by the nature of the soil (Herbich 1975), thus making the preliminary soil description essential.

The U.S. Army Corps of Engineers, through their Dredging Research Program, and the Permanent International Association of Navigation Congresses (PIANC) are attempting to address the need for common descriptors. Spigolon (1988), working with the Corps of Engineers, proposed the soil classification groups shown in Figure 5. He suggested that further research be performed to determine soil property limits for use in this classification system, as shown in Figure 6. However, no definite descriptor has been proposed with these properties.

Current practice

Dredging plans ordinarily show detailed alignment and dimensions and normally include boring logs. However, often the boring logs are incomplete, a factor leading to misunderstandings and disputes (Hudson 1970). That is, the soil information provided typically does not infer production since the tests and classification do not relate well to the processes involved in dredging (Verhoeven, Jong, and Lubking 1988). Furthermore, most contracts contain clauses such that the material described in the contract is not guaranteed, and removal of other materials within the project bounds must be performed at the expense of the dredging contractor. This has two effects. First, the owner is unsure of how difficult the task may be and, therefore, can only speculate what a fair price for the project might be. The owner may also be unclear how to best handle the dredged material. Second, the dredging contractor must gamble to price the job because little relevant information to estimate his costs is available in advance. Usually, the owner pays a substantial premium for this risk. Predicting the cost of a dredging project is directly related to the available knowledge of the geotechnical conditions. Reliable descriptors, which are associated with relevant geotechnical properties, should enable accurate predictions of a site's dredgeability.

Group B:	Boulders and Cobbles. Significant amount of boulders, cobbles, and large gravel; usually insignificant amounts of nonplastic fines.
Group L:	Loose Granular. Loose, inorganic, free-flowing soils with nonplastic fines; easily "sucked" (loosened and removed) hydraulically; easily transported in a pipeline slurry.
Group F:	Friable Granular. Dense, free-flowing soils and low plasticity friable soils; require cutting or ripping to dislodge, but will disintegrate during hydraulic removal; will enter easily into a pipeline slurry.
Group M:	Fluid Cohesive. "Muds"; exist in suspension as a slurry; very low density and very high water content; exhibit some plasticity when dried; typically clayey silts and/or clays; may contain some fine sand.
Group C:	Heavy Cohesive. Massive, coherent soils; clays of medium to high plasticity; can only be loosened and removed by mechanical methods; form clods and clay balls; often sticky when water content is high; may be difficult to cut.
Group P:	Problem soils. Peat and organic soils; could be extended to include cemented soils and other "problem" soils.

Figure 5. Soil classification groups for dredgeability (Spigolon 1988)

- Site classification of soil
  - Maximum grain size
  - Dominant type of soil, i.e., gravel, sand, clay, etc.
  - Modifiers to the dominant soil type to show gradation
  - Plasticity (of cohesive soils; of fines in granular soils)
- Grain shape and hardness of granular soils
  - Color and odor, if any
  - Structure of intact soil
  - Presence of peat, other organics, cementation, debris
- Compactness of granular soils - relative density
- Consistency of cohesive soils - unconfined compressive strength
- In situ density
- Rheologic properties of slurry at various densities
- Rate of sedimentation in salty water
- Bulking factor

Figure 6. Suggested soil properties for use in descriptors (Spigolon 1988)

Research in descriptor development

To develop useful geotechnical descriptors, uniformly acceptable investigation and testing procedures must be introduced. The tests must be simple so that they can be conducted rapidly and inexpensively by commercial

laboratories. Testing procedures should be related to the characteristics that are responsible for soil behavior when dredged. For example, procedures for establishing the dredgeability of sands and silts were presented by Leshchinsky (1990), based on effective internal angle of friction, relative density, and permeability of sands and silts. Behavior of sands and clays is completely different under dredging conditions. Consequently, the descriptor developed for noncohesive soil is meaningless for cohesive ones.

The Dutch dredging industry has a well-established and productive dredging research program. Research conducted at Delft Hydraulic Lab has apparently produced tests that are used by the Dutch dredging industry to predict rate of degradation of clays. Unfortunately, the relevant material properties and test procedures used by the Dutch are not available because of proprietary restrictions. It is known that there are two types of tests used; namely, a shaking table test and a rotor test (Lord and Issac 1988). The shaking table test attempts to simulate the mechanical impact undergone by clay lumps during the various phases of hydraulic transport. The experimental results are used to determine the coefficients in a differential equation that describes the rate of lump disintegration.

Research has also been done by Syncrude Ltd. (Lord and Issac 1988), an oil shale mining company in Alberta, Canada. This research was motivated by the need to dredge large volumes of overburden above oil-bearing shale. Researchers at Syncrude used a rotating drum to predict rate of degradation of material being dredged. Experimental results were then compared with actual dredging results at the site. It was found that accurate predictions of actual degradation were achieved when the same transport fluid used by the dredge was used in the test, and lumps size tested where the same as those cut by the cutterhead (Lord and Issac 1988).

Investigation procedures

Improvements in investigation procedures also need to be made. Ideally, investigations should be such that sufficient information on soil conditions in the area to be dredged are available. Continuous soil sampling and testing may be impractical. However, the expense of conducting a thorough investigation can be justified if useful information is generated. For economy and simplicity, disturbed samples can be taken with minimum difficulty. This type of sample is adequate for determination of Atterberg Limits (ASTM D-4318) and conducting the Proctor Compaction Test (ASTM D-698). The Vane Shear Test (ASTM D-2573) is also a simple test to determine the un-drained shear strength of soils. This may relate well to soil resistance to the cutterhead excavation.

Methods for determining underwater in situ soil density are more difficult to carry out. One way this can be done is by taking an undisturbed soil sample, but this is relatively difficult and expensive to do. Approximate correlations between the Standard Penetration Test (ASTM D-1586) and clays'

consistency are available (e.g., Figure 7). This consistency is related to the overconsolidation ratio and, indirectly, to the density. The Cone Penetration Test (ASTM D-3441) measures soil shear strength and may provide indirect information about density level as well. Perhaps the most promising method for determining soil density efficiently has been developed by Delft Hydraulics Lab (Dunlap 1988). This method uses a nuclear probe towed underwater by a boat. The method is significant because it provides a continuous in situ soil density readout, which can provide valuable information in determining the dredgeability of soil throughout the project site. For clayey soil, an estimation of field density can be achieved through measurement of in situ water content (ASTM D-2216) and specific gravity of solids (ASTM D-854). For a fully saturated soil, the dry density then is:

$$\gamma_d = \frac{G\gamma_w}{1 + G\,w}$$

where

γ_d = dry unit weight of soil

γ_w = unit weight of water

G = specific gravity of soil solid particles

w = moisture content

Basic Soil Type	Density or Consistency	Range of Standard Penetration Resistance[1]	Range of Unconfined Compressive Strength $(q_u)^2$
Cohesionless	Very loose	Less than 4 per foot	Not applicable
	Loose	4 to 10	Not applicable
	Medium dense	10 to 30	Not applicable
	Dense	30 to 50	Not applicable
	Very dense	Greater than 50	Not applicable
Cohesive	Very soft	Less than 2 per foot	Less than 0.25 ton/sq ft
	Soft	2 to 4	0.25 to 0.5
	Medium stiff	4 to 8	0.5 to 1.0
	Stiff	8 to 15	1.0 to .0
	Very stiff	15 to 0	2.0 to 4.0
	Hard	Greater than 30	Greater than 4.0

1 Number of blows from 10-lb weight falling 30 in. to drive 2-in. OS, 1-3/8-in. ID, sampler.
2 q_u may also be approximated using a pocket penetrometer or Torvane shear apparatus.

Figure 7. Soil density and consistency based on Standard Penetration Test (EM 1110-2-1907)

From the Proctor compaction test, one can estimate the relative degree of compactness of the in situ clay. The results of this study indicate that the rate of clay lump degradation can be estimated based on the aforementioned properties; i.e., Atterberg limits and relative compactness (or undrained shear strength).

3 Materials, Equipment, and Testing Procedure

Materials

Samples were assembled by using a mixture of the two clays, kaolinite and bentonite. The bentonite was General Purpose Granular, GPD 30, Western Bentonite, manufactured by the American Colloid Company of Skokie, Illinois. The kaolinite was Pulverized Kaolinite, C.A.S. No. 1332-58-7, manufactured by the Feldspar Corporation, Edgar, Florida. These two types of clay were selected for use in testing because of their wide extremes in plasticity. Consequently, by varying the proportions of kaolinite and bentonite in a mixture, a wide range of simulated clays could be tested.

Material properties

Prior to actual testing, selected properties of kaolinite, bentonite, and their mixture were determined. These properties were: Atterberg limits, maximum dry density, and Torvane shear strength.

Atterberg limits for clay samples formed from different proportions of kaolinite and bentonite in mixture were determined using ASTM D-4318, "The Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils." Test results for Atterberg limits are given in Table 1. Figure 8 shows the Atterberg limits versus percent bentonite in mixture. It can be seen that as the proportion of bentonite in the mixture increases, the liquid limit (LL) increases drastically while the plastic limit (PL) increases very little. Subsequently, the plasticity index (PI), which is the difference between the liquid and plastic limits, increased quickly as the proportion of bentonite in the mixture increased. The plasticity index varied from 25 percent for only kaolinite in mixture, to 568 percent for only bentonite in mixture.

Maximum dry density for different proportions of kaolinite and bentonite in the mixture was determined using the standard Proctor compaction test, ASTM D-698, "The Standard Test Method for Moisture Density Reltions of Soils Using 4.4-lb Hammer and 12-in Drop." Figure 9 shows the variation of

Table 1
Atterberg Limit Test Results

Percent Bentonite in Mixture with Kaolinite	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)
0.0%	31	56	25
2.5%	32	59	27
3.5%	32	61	29
5.0%	33	66	33
10.0%	33	87	54
20.0%	34	129	95
40.0%	36	215	179
60.0%	39	314	275
80.0%	43	438	396
100.0%	49	617	568

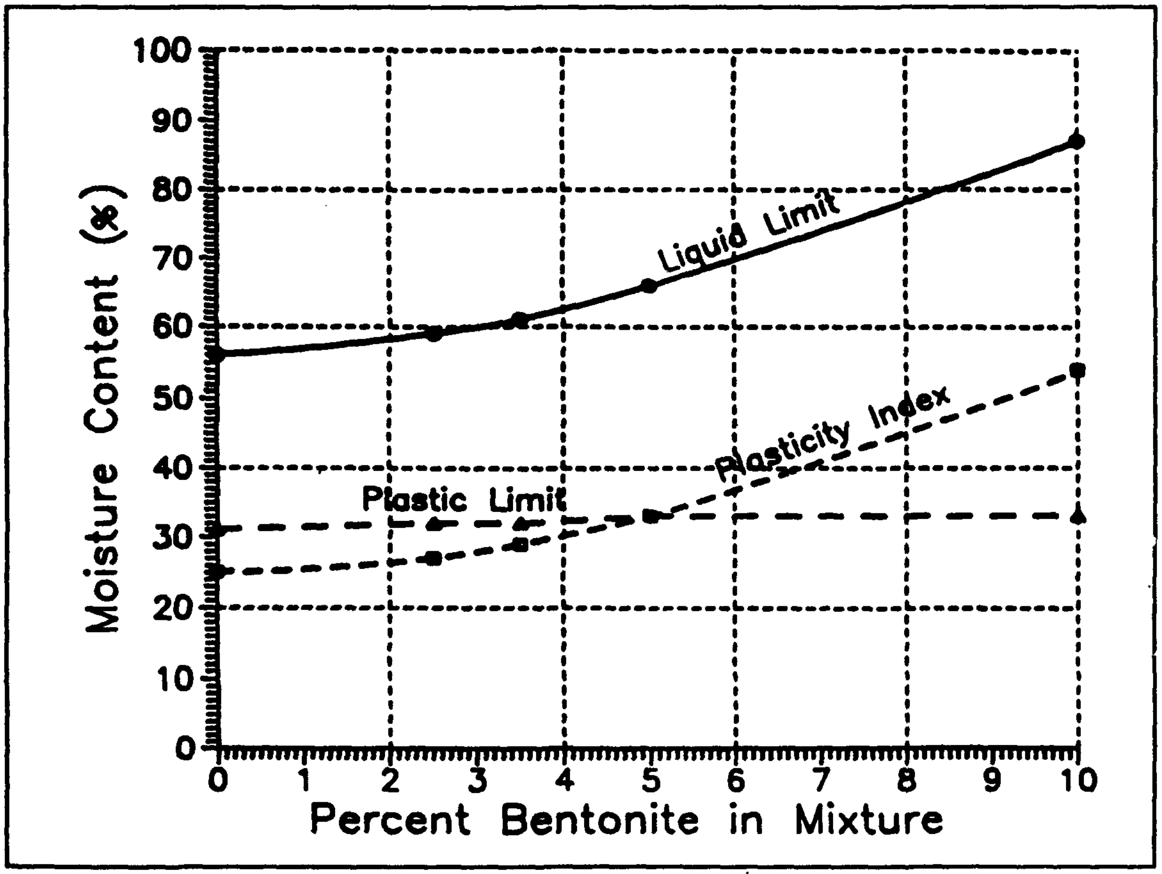


Figure 8. Liquid limit, plastic limit, and plasticity index versus percent bentonite

maximum dry density versus percent bentonite in the mixture. The maximum dry density for only kaolinite in the mixture was 89.2 pcf. The maximum dry density for 80 percent bentonite in mixture was 74.8 pcf. Optimum moisture

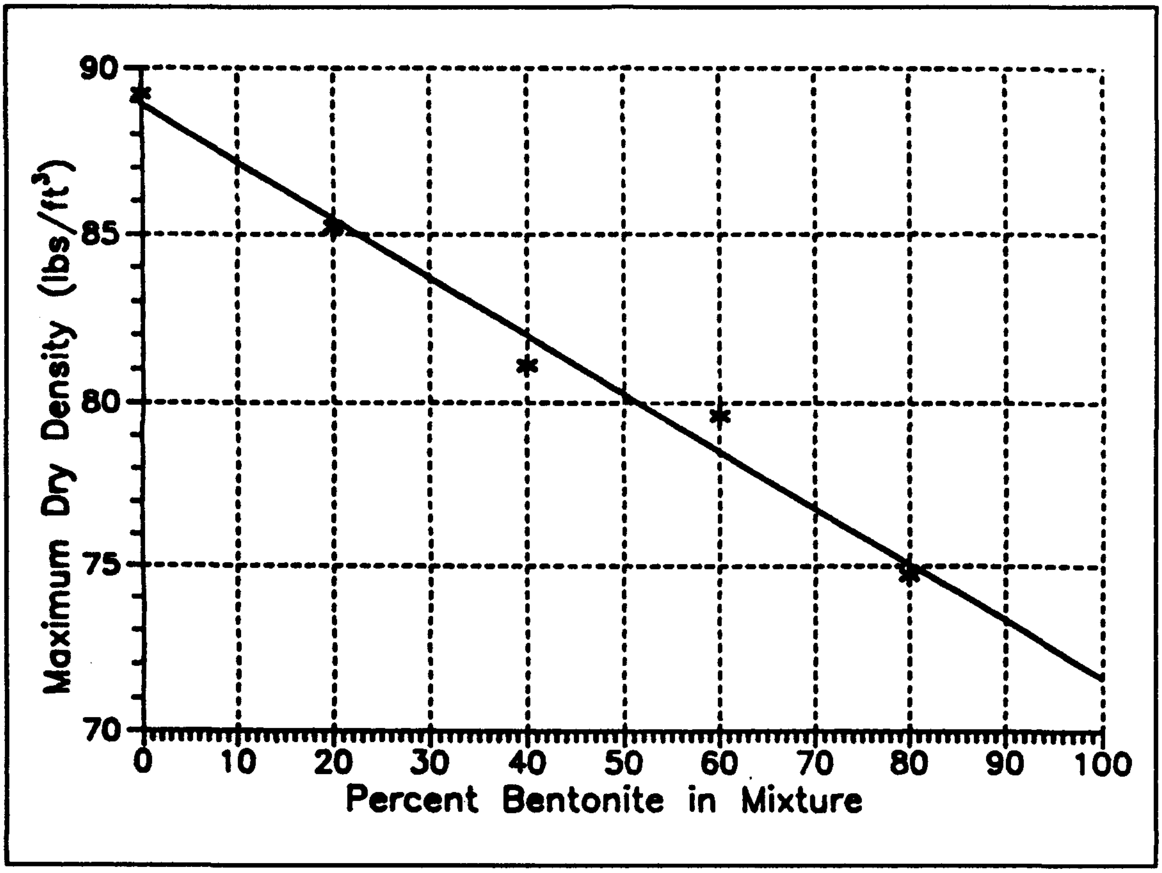


Figure 9. Maximum dry density versus percent bentonite

content for maximum standard Proctor, corresponding to each mixture, is shown in Figure 10.

To assess the shear strength, specimens were tested with a Torvane shear strength apparatus, Model CL-600A, Soil Test Inc. Clay specimens were compacted in a Proctor mold to their maximum dry density and submerged in water for four days. The specimens were then extracted from the mold, sliced open to reveal their interior, and sheared with the Torvane. Figure 11 shows the measured shear strength versus percent bentonite in the mixture. Clearly, the shear strength decreases as percent bentonite in the mixture increases.

Material classification

Kaolinite and bentonite clays were classified in accordance with the Unified Soil Classification System (USCS) using ASTM D-2487, "The Standard Test Method for Classification of Soils for Engineering Purposes." Kaolinite and those mixtures with a small proportion of bentonite are consistently classified as MH, a silty clay. Pure kaolinite can be classified as the boundary between lean and fat clay, and in the context of this work it was considered as a lean

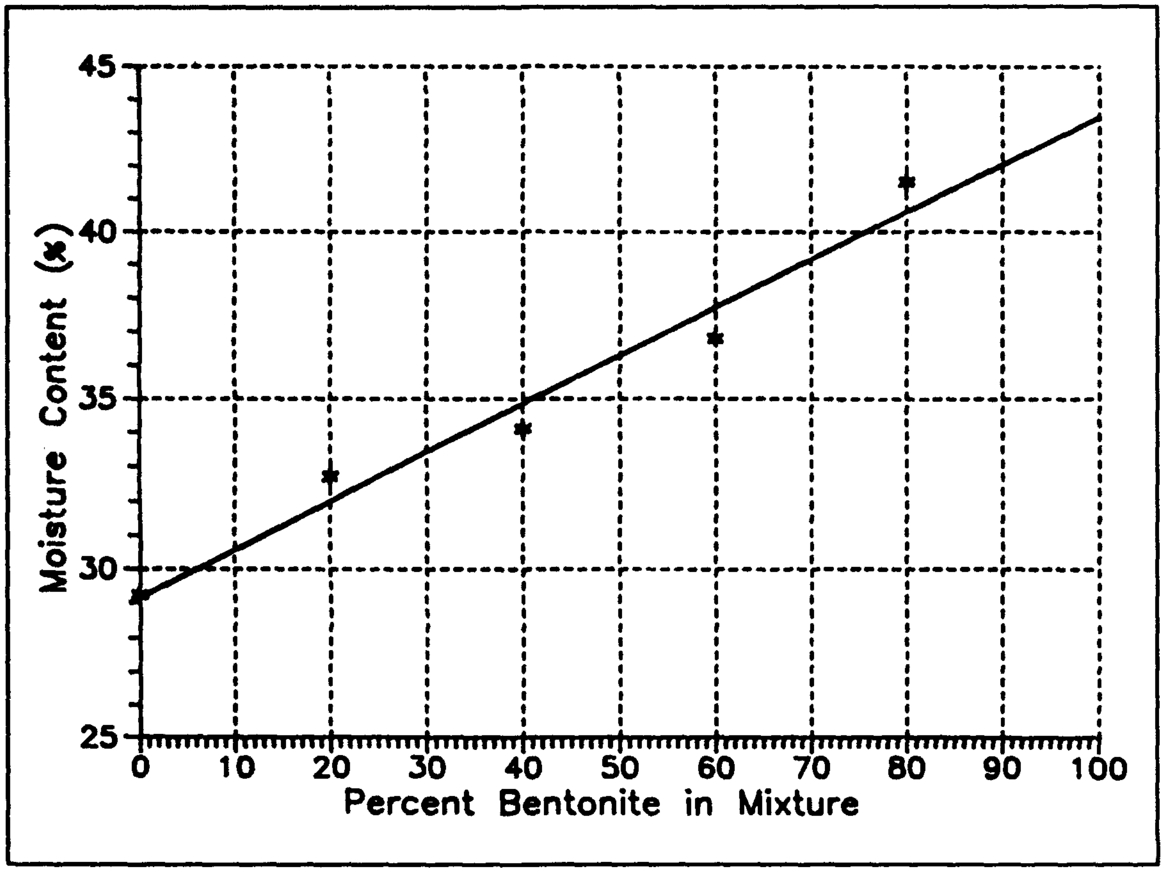


Figure 10. Optimum moisture content for maximum density

clay. Kaolinite is a fairly fragile clay, but plastic enough to be easily molded and formed. Conversely, bentonite is classified as CH, a fat clay, by the USCS. Bentonite has a very high degree of plasticity and liquid limit. It is extremely sticky and hard to work with.

Test Facilities

Clay samples with known and carefully controlled properties were prepared and tested to determine how friable they are when undergoing hydraulic transport such as occurs in a dredge line. The forces considered in planning the experiments which may cause degradation of clay lumps during hydraulic transport are as follows:

a. The drag forces exerted by the water on the clay lumps while transporting it hydraulically. This causes an erosive effect on the solid lump similar to water running off a slope.

b. The turbulence of the water necessary to hold the clay lump in suspension.

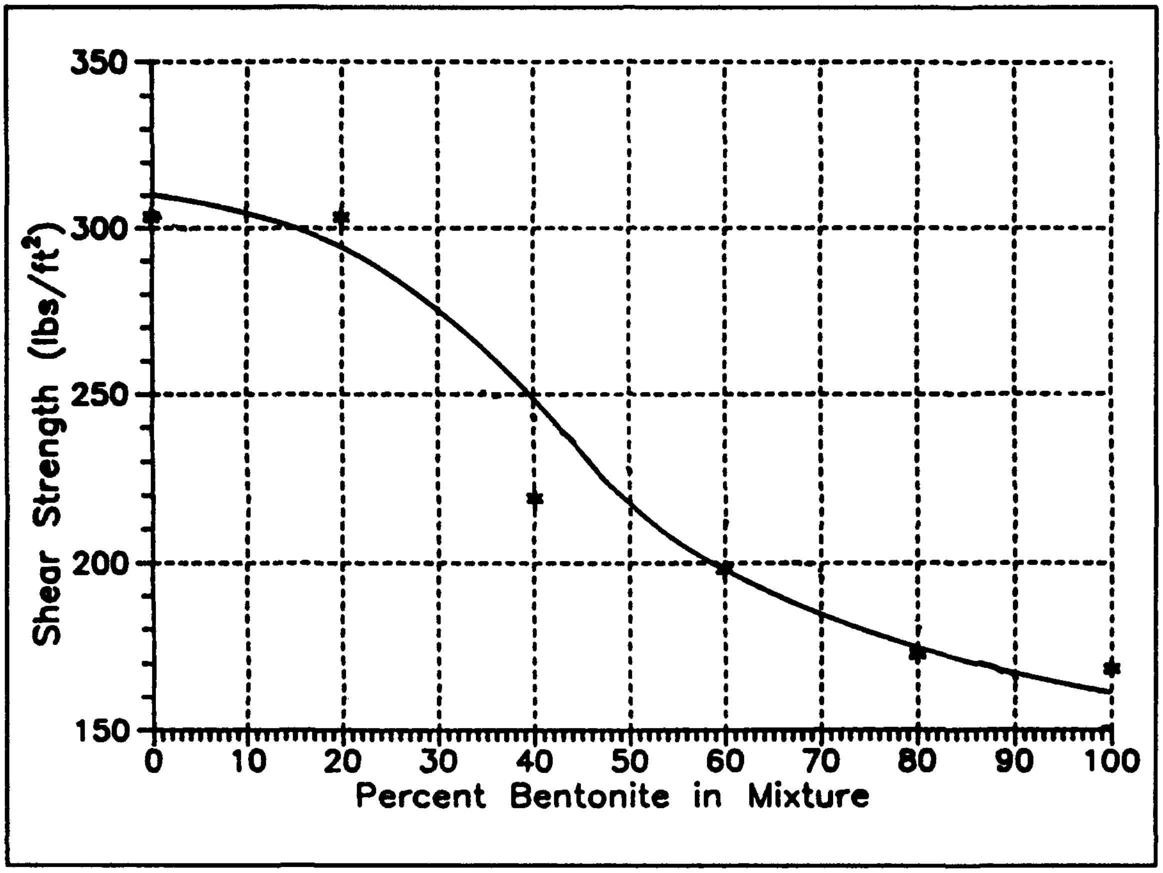


Figure 11. Undrained shear strength versus percent bentonite

c. The effect of relative movement of coarse-grained particles and the clay lump.

d. The effect of clay lumps colliding against each other, as well as the sides of the dredge pipeline. This may cause degradation in low plasticity clays, but in higher plasticity clays may result in clay balling.

Obviously, it is not practical to construct a true dredge line, the length of which might extend for several miles. As an alternative, two different test setups were used to simulate the hydraulic transport effect. These setups are referred to as the spin and drum tests.

Spin test

The spin test consisted of a tripod stand with a variable speed electric motor mounted on top (Figure 12). A shaft connected the motor to a clamp where the clay specimen was secured in place between two pedestals (Figure 13). The pedestals were greased with petroleum jelly to facilitate removal of the specimen at the end of the test. The clay specimen, clamped in place,

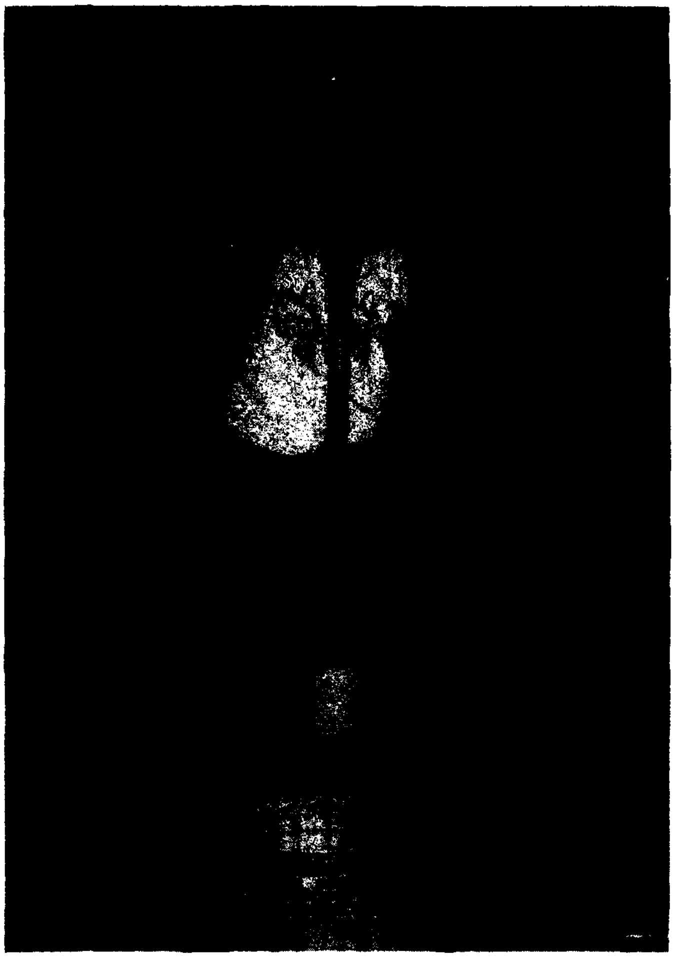


Figure 12. Components of spin test device

was then lowered into a 20-gal waterproof container, which was partially filled with clear potable tap water. The motor was then operated at a constant speed, rotating the submerged specimen (Figure 14) for some selected time increment ranging up to 60 min. After the selected exposure time to spinning had elapsed, the intact portion of the specimen was lifted out of the water (Figure 12) and removed from the clamp. This clay specimen was then dried (Figure 15) and weighed to determine the effect of spinning on degradation. The intact specimen's final weight expressed as a percentage of its initial weight is referred to as degradation. Additional technical details are given by Richter (1991).

Normally, three specimens with identical properties were tested at a constant velocity at three different spinning times. Each specimen tested produced a point on a graph representing the degradation of the specimen caused by spinning versus time. This allowed a line to be drawn through the three points. The slope of this line represents the rate of lump degradation for a given set of material properties at a given spinning velocity. Velocity in this case is expressed as the tangential velocity of the specimen, where the radius is

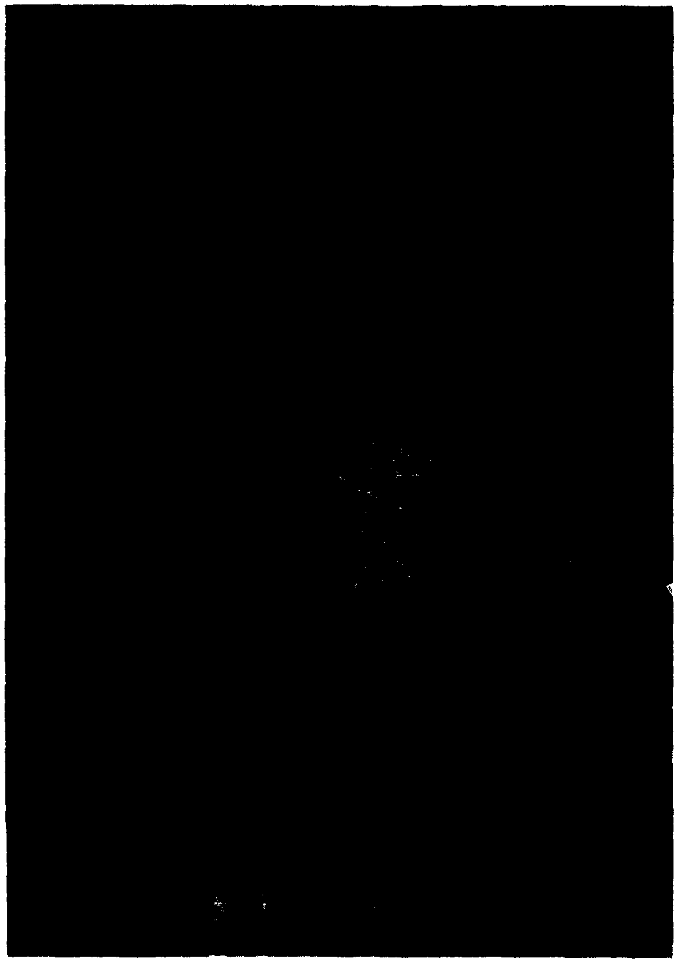


Figure 13. Clamped specimen

taken as 2 in., i.e., the initial radius of the specimen. Tangential velocities used in the spin test were 1 ft/sec and 2.5 ft/sec. These velocities signify the relative velocities between the clay lumps and the fluid dragging them.

Turner (1984) points out that normal suction line velocities used in dredging range from 6 ft/sec to 25 ft/sec. Clay lumps, however, settle in the bottom of a dredge line and are transported as a moving bed. The clay lumps therefore travel more slowly than the transport fluid. It is felt that the velocities used in the spin test closely represent the relative velocities between the clay lumps and the fluid adjacent to the lumps in the dredge line. The degradation resulting from these relative velocities was simulated and studied.

Smooth drum test

The smooth drum test consisted of a sheet metal drum (16-in. diam and 16-in. length-see Figure 16) with screened ends. One end had an opening to allow a prepared clay specimen to be inserted and removed (Figure 17). The

Figure 14. Spin test in progress

drum was mounted on its side and held in place by ball bearing supports. The drum was suspended in a tank, filled with clear, potable tap water, such that the drum was about half submerged (Figure 17a). The drum was connected to an electric motor (Figure 16), by a shaft running through its center, and could be rotated at varying speeds.

A clay specimen was inserted (Figure 17b) and the drum was then rotated at a constant speed (Figure 18a) for some selected time increment ranging up to 60 min. After the selected exposure time to agitation had elapsed, the motor was stopped and the intact portion of the clay specimen was removed from the drum (Figure 18b). The specimen was then dried and weighed (Figure 19) to determine the effect of agitation.

Again, as in the spin test, three specimens with identical properties were tested at a constant velocity using three different exposure times. Each specimen tested yielded results that could be expressed as a point on a graph representing the degradation of the specimen caused by the drum agitation versus time. This allowed a line to be drawn through the three points representing

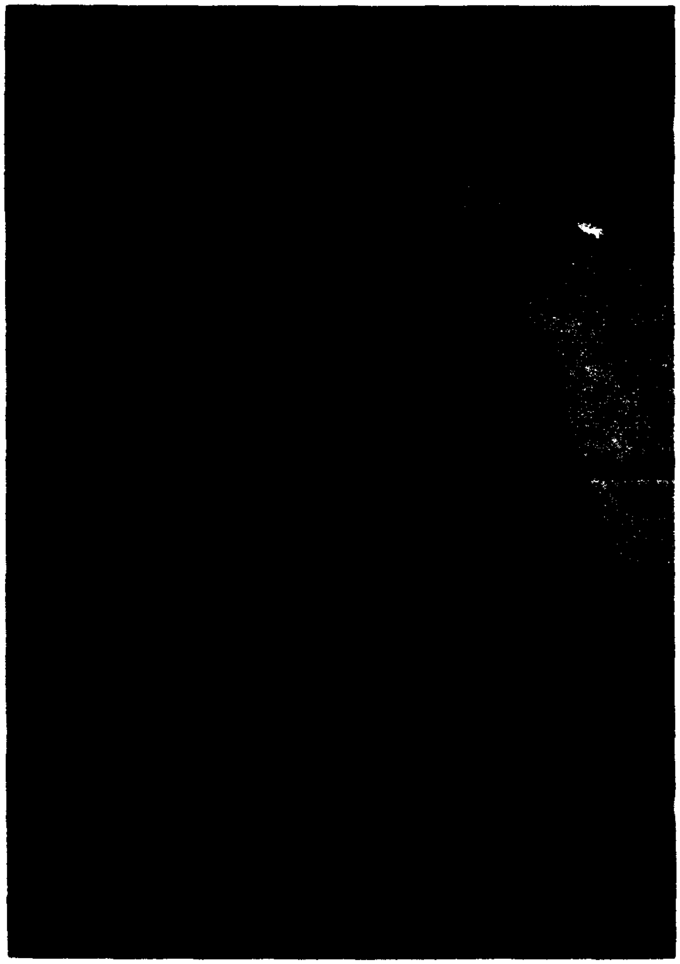


Figure 15. Dried intact portion of tested specimen

the rate of lump degradation for a given set of material properties at a given velocity. Velocity in this case is expressed as the tangential velocity of the rotating drum. The tangential velocity used in the smooth drum test was 2.5 ft/sec. The smooth drum test closely simulated all hydraulic transport effects responsible for clay lump degradation as previously described, except for the effect of coarse-grain particles and rough pipeline wall conditions.

Rough drum test

In hydraulic transport of clay, some quantity of coarse particles, as well as the rough sides of the pipeline, would likely be encountered. These would have an abrasive effect on clay lumps in transport. To simulate this abrasive effect, the drum was next lined with coarse sandpaper. The testing procedure was otherwise the same as for the smooth drum test. Tangential velocities used in the rough drum test were 2.5 ft/sec, 5 ft/sec, and 7.5 ft/sec. This provided another set of friability results, accounting for all hydraulic transport effects causing clay lump degradations.

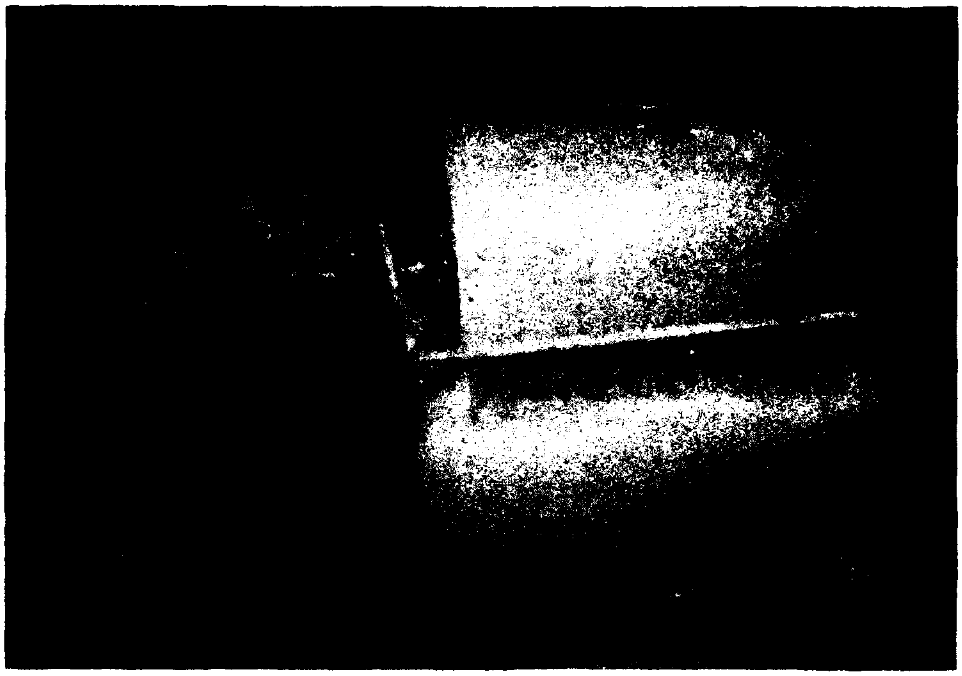


Figure 16. View of drum test setup

Sample Preparation and Testing Procedure

Sample preparation and test conduct are described in this section. The tendency for friability of clay under hydraulic transport conditions was studied based on material plasticity, degree of compaction, relative speed between the transport fluid and solids, and exposure time. A chart outlining the various tests conducted is shown in Figure 20.

Preparation of clay specimens

Clay specimens were prepared using various proportions of bentonite in mixture with kaolinite. By carefully controlling the proportion of bentonite in the mixture, the effect of varying the plasticity index could be realized. It was found that varying the bentonite content in the mixture from 0 percent to 10 percent produced plasticity indices which ranged from 26 percent to 54 percent. This range of PI was sufficient to identify trends and to establish correlations.

The bentonite/kaolinite clay mixture was produced as follows. The mixture was first proportioned according to the desired PI. The mixture was then thoroughly blended, kaolinite in its dry powder form and bentonite in its granular form. A controlled amount of water was then added to the mixture. The amount of water added to a particular mixture was that found to produce the optimum moisture content for maximum standard Proctor compacted dry

(a) (b)

Figure 17. Drum test: (a) submergence in water, and (b) placement of specimen

(a)

(b)

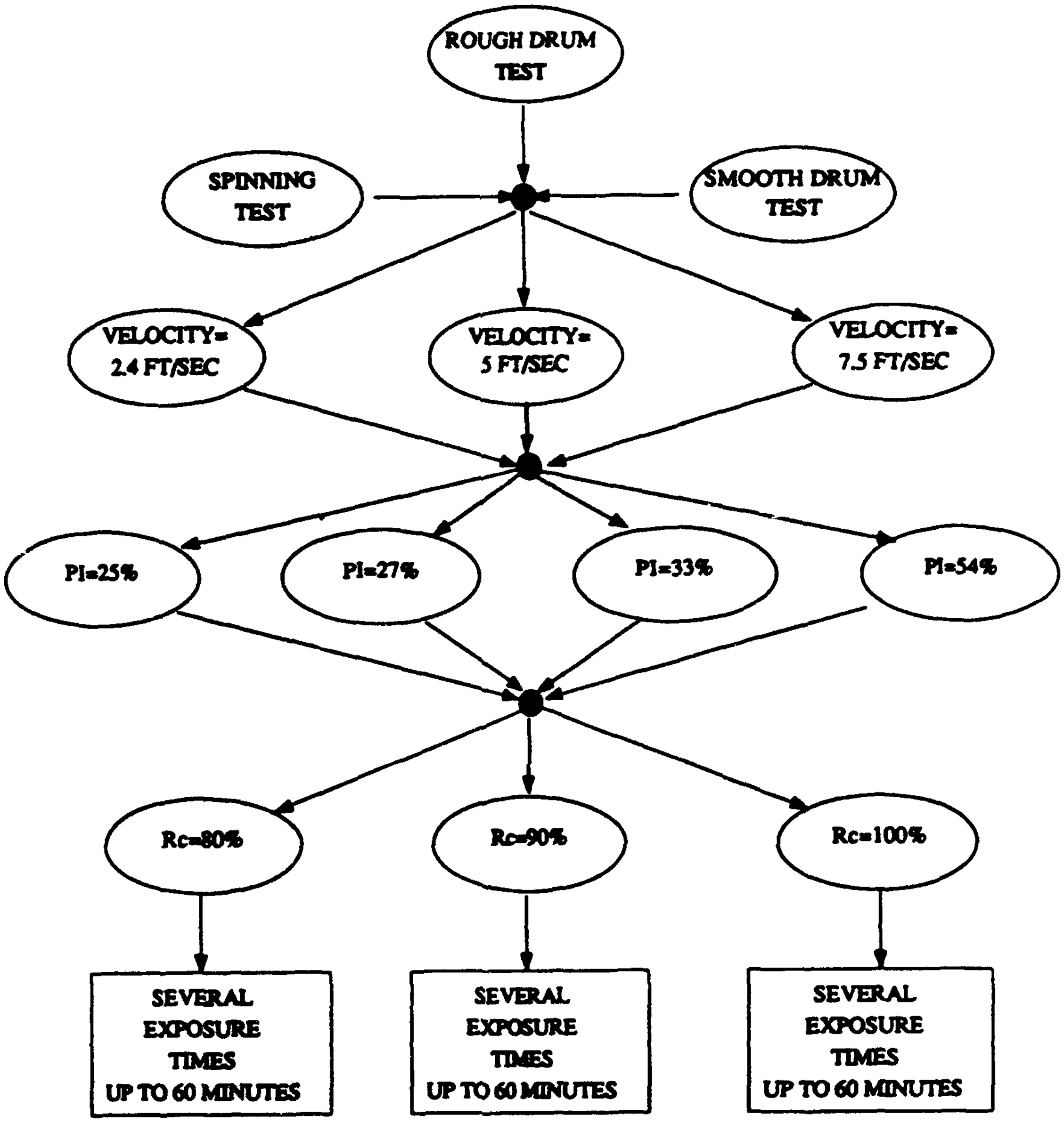
Figure 18. Drum test: (a) in progress, and (b) removal of intact portions of specimen

Figure 19. Dried intact portion of specimen

density. The moist clay was then thoroughly mixed by hand to a uniform consistency.

Compaction of clay specimens

Along with plasticity, it was important to study the effect of density on friability. Clay specimens were prepared for testing by statically compacting them in a standard Proctor compaction mold (Figure 21). The procedure for compacting specimens was as follows: a portion of clay prepared to its optimum moisture content was weighed out and placed in the standard Proctor compaction mold with its collar on; the weight of clay placed in the mold was controlled by the desired density, or relative compaction (*Rc*); the mold was then placed in a press and the specimen was statically compacted to a volume of 1/30 cu ft (e.g., Figure 22a). Depending on the amount of material placed in the mold, the specimen was statically compacted to 80 percent, 90 percent, or 100 percent of maximum standard Proctor. The compacted specimen was then extruded (Figure 22b), weighed, and tested.



Legend: PI=Plasticity Index
Rc=Compaction relative to maximum standard Proctor

Figure 20. Summary of tests conducted

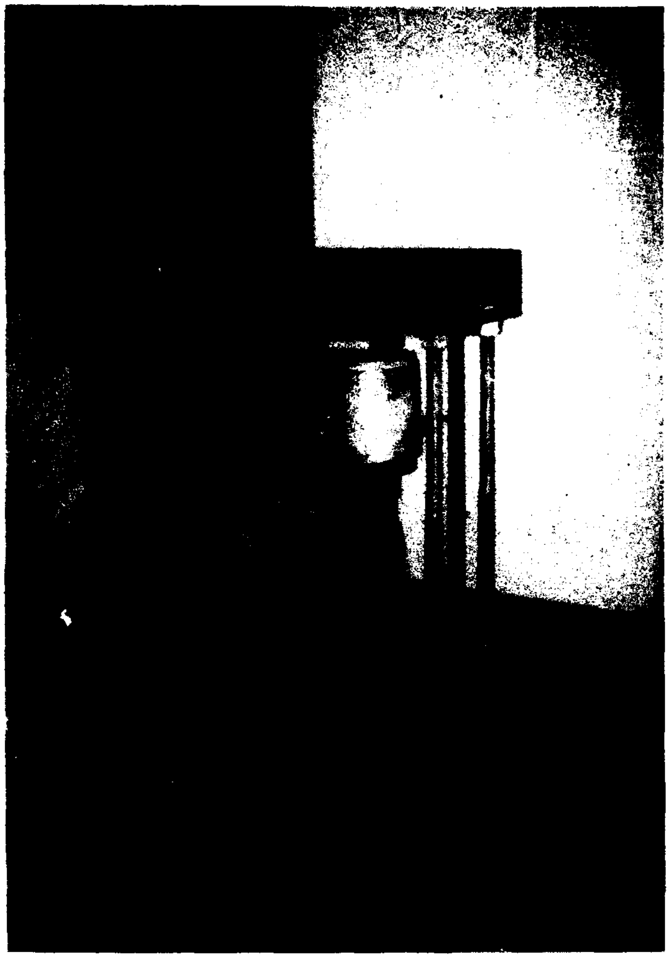
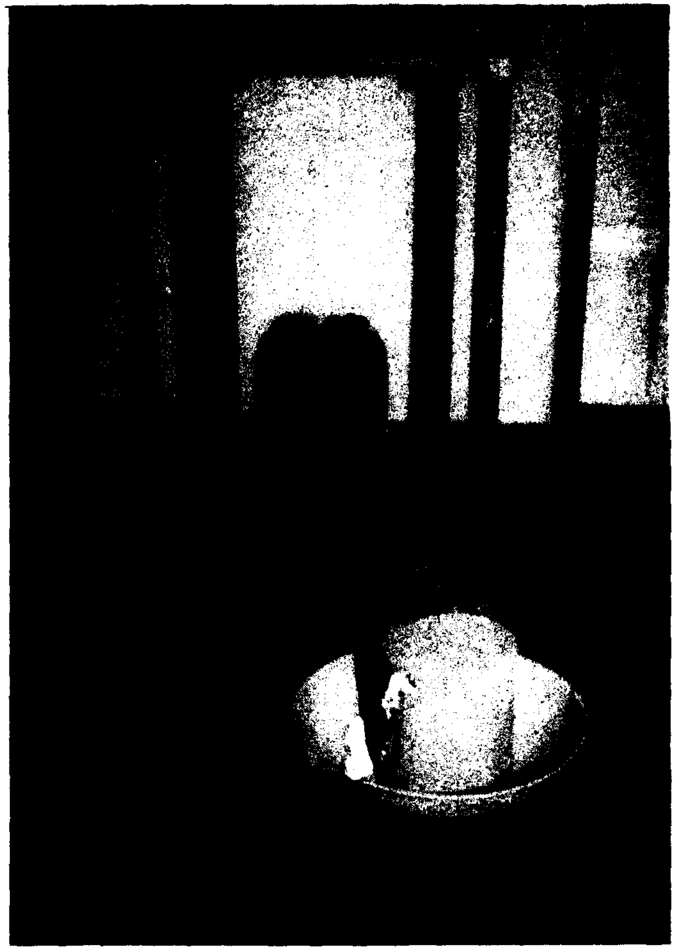


Figure 21. Static compaction of clay mixture

Spin and drum tests

The spin and drum devices were designed to simulate the forces imposed on a clay lump while being transported hydraulically. The effects of these forces are influenced not only by the material properties of the clay lumps, but also by the velocity and turbulence of the lump in transport, the relative velocity of the transporting fluid versus the lump, and the length of time the lump is in transport. Because it was desired to establish a trend of how these forces affect the rate of lump degradation, the rotation speed and specimen exposure time were varied as well. The results of the tests are given in Chapter 4.

(a)



(b)

Figure 22. Compacted specimen: (a) in Proctor mold, and (b) extruded

4 Results of Testing Program

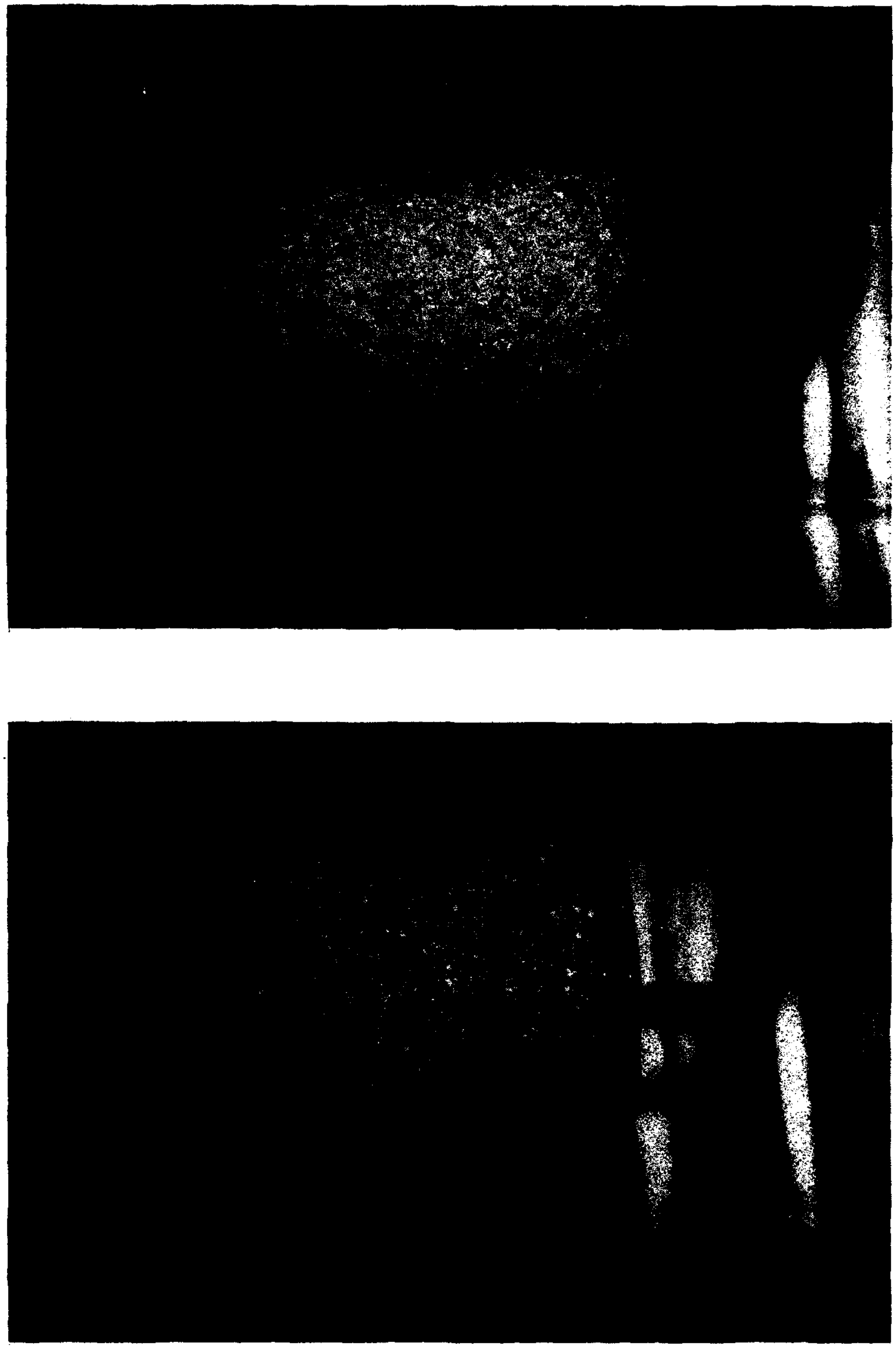
Test Results

The report of test results is divided into three categories: spin test, smooth drum test, and rough drum test. Procedures for conducting these tests and descriptions of their relevance to clay lump degradation during hydraulic transport are contained in Chapter 3. Appearance of typical specimens after both the spin and drum tests is shown in Figures 23, 24, and 25.

All results in this chapter are presented as percent of remaining intact material versus spinning or drum exposure time. Remaining intact material is a percentage representing the final dry weight of the intact specimen after exposure divided by the initial dry weight of the specimen. Test result figures show data points, along with their best fit straight line. The slope of this line represents the rate of lump degradation under the imposed testing conditions. It should be stated that because of the scattering of the data points, a straight line seems to be the most practical approximation.

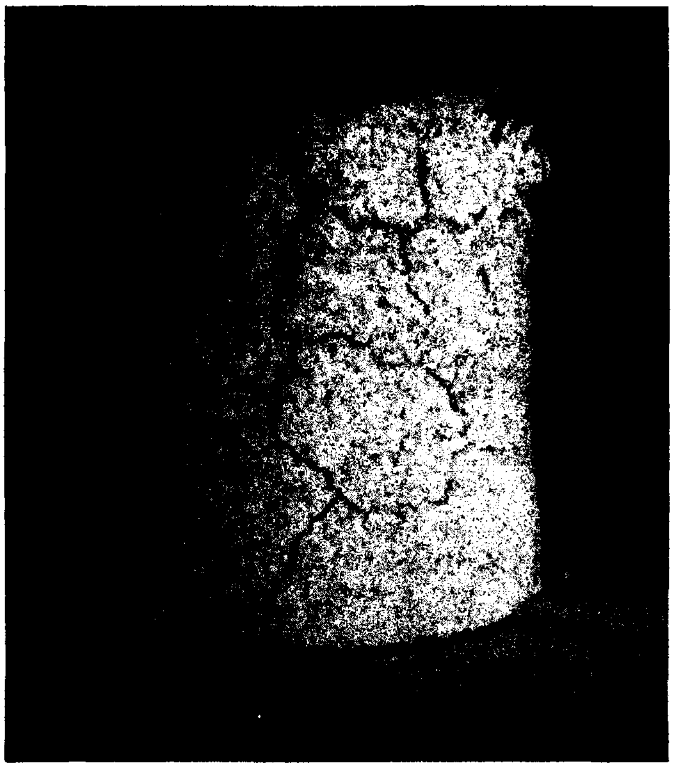
Spinning test

The spinning test simulated mainly the degradation effect of the transport fluid, which flows faster relative to the clay lump and, hence, drags the dredged material. The spinning test was conducted at two tangential velocities: 1 ft/sec and 2.4 ft/sec. At each velocity, specimens at four different plasticity indices (PIs) were tested. These PIs were: 25 percent, 27 percent, 33 percent, and 54 percent. For each PI tested, three degrees of relative compaction (*Rc*) were used: 80 percent, 90 percent, and 100 percent. Spin test results conducted at a tangential velocity of 1 ft/sec are shown in Figures 26 through 29. Spin test results conducted at a tangential velocity of 2.4 ft/sec are shown in Figures 30 through 33.



(a) (b)

Figure 23. Appearance of specimens after: (a) short spinning time, and (b) longer spinning time



(a)

(b)

Figure 24. Dried spin test specimens: (a) closeup view, and (b) assortment

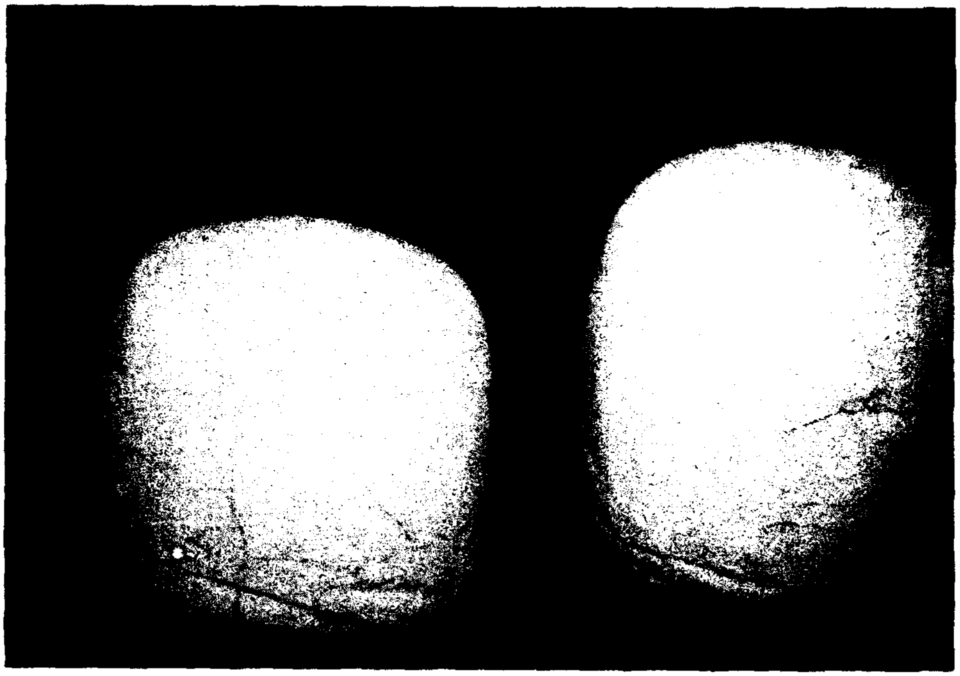


Figure 25. Dried drum test typical specimens

Smooth drum test

The smooth drum test simulated the turbulence of the transport medium (i.e., water and clay lumps) as they move through the dredge line. It also simulated the relative velocity of the transport medium to the clay lump, and the colliding effect of the clay lump against the sides of the dredge line. The smooth drum test was conducted at one tangential velocity, 2.5 ft/sec. Specimens at four different plasticity indices were tested: 25 percent, 27 percent, 33 percent, and 54 percent. For each PI tested, three deg of relative compaction were used: 80 percent, 90 percent, and 100 percent. Smooth drum test results are shown in Figures 34 through 37.

Rough drum test

The rough drum test simulated the same hydraulic transport effects causing lump degradation as the smooth drum. It also simulated the effect of coarse grain particles being carried by the transport fluid and the rough sides of the dredge pipe. The rough drum test was conducted at three tangential velocities: 2.5 ft/sec, 5 ft/sec, and 7.5 ft/sec. At each velocity, specimens at four different plasticity indices were tested: 25 percent, 27 percent, 33 percent, and 54 percent. For each PI tested, three degrees of relative compaction were used: 80 percent, 90 percent, and 100 percent. One exception was the test at 5 ft/sec, where Rc = 90 percent was not included. Rough drum test results conducted at a tangential velocity of 2.5 ft/sec are shown in Figures 38 through 41. Test results conducted at a tangential velocity of 5 ft/sec are shown in

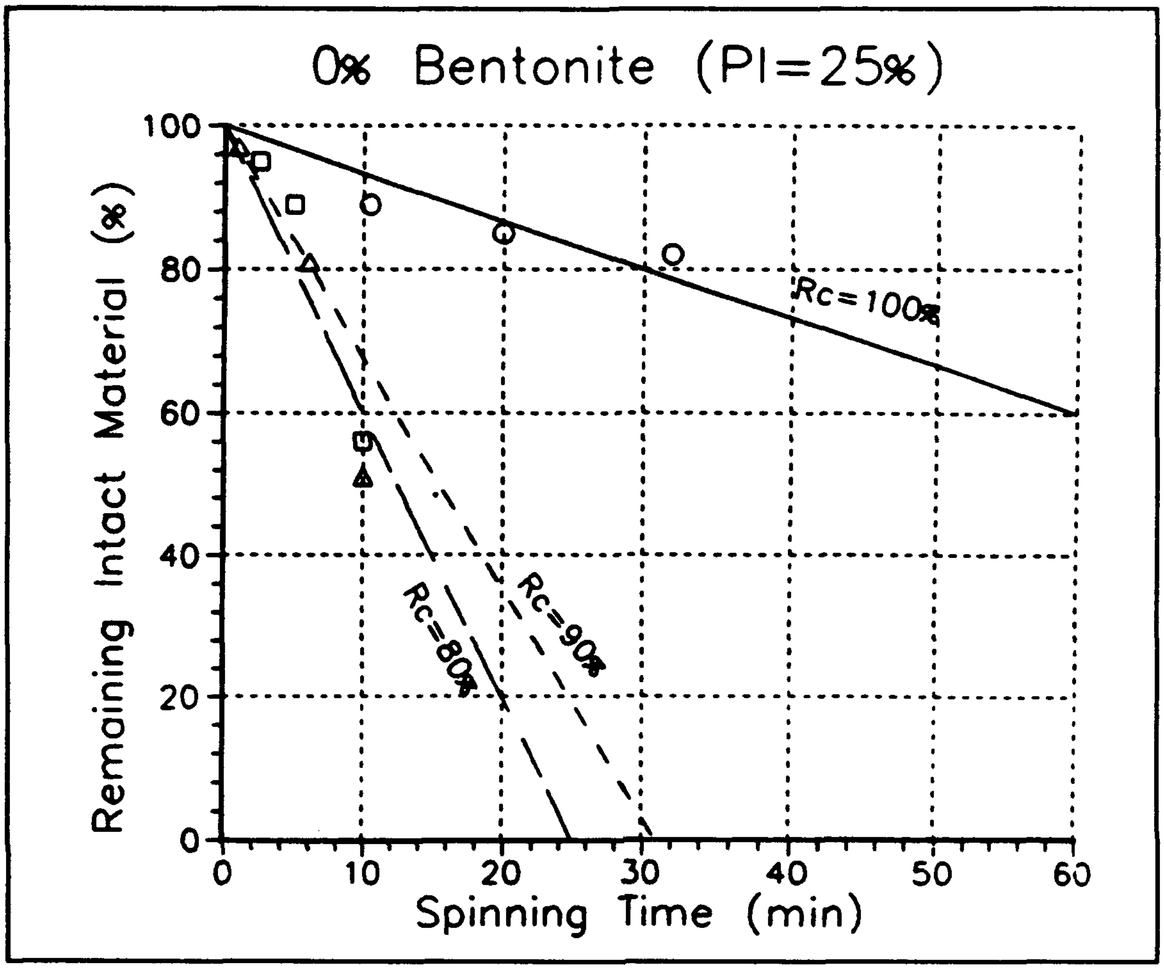


Figure 26. Spin test (V = 1 ft/sec, PI = 25 percent)

Figures 42 through 45. Results obtained at a tangential velocity of 7.5 ft./sec are shown in Figures 46 through 49.

Summary

Spin, smooth drum, and rough drum test results can be summarized as follows:

a. A straight line seems to fit reasonably well the measured data points (i.e., percent of intact clay versus testing time). The slope of the line represents the rate of lump degradation.

b. Material degradation is dependent on exposure time, PI, *Rc*, and relative velocity.

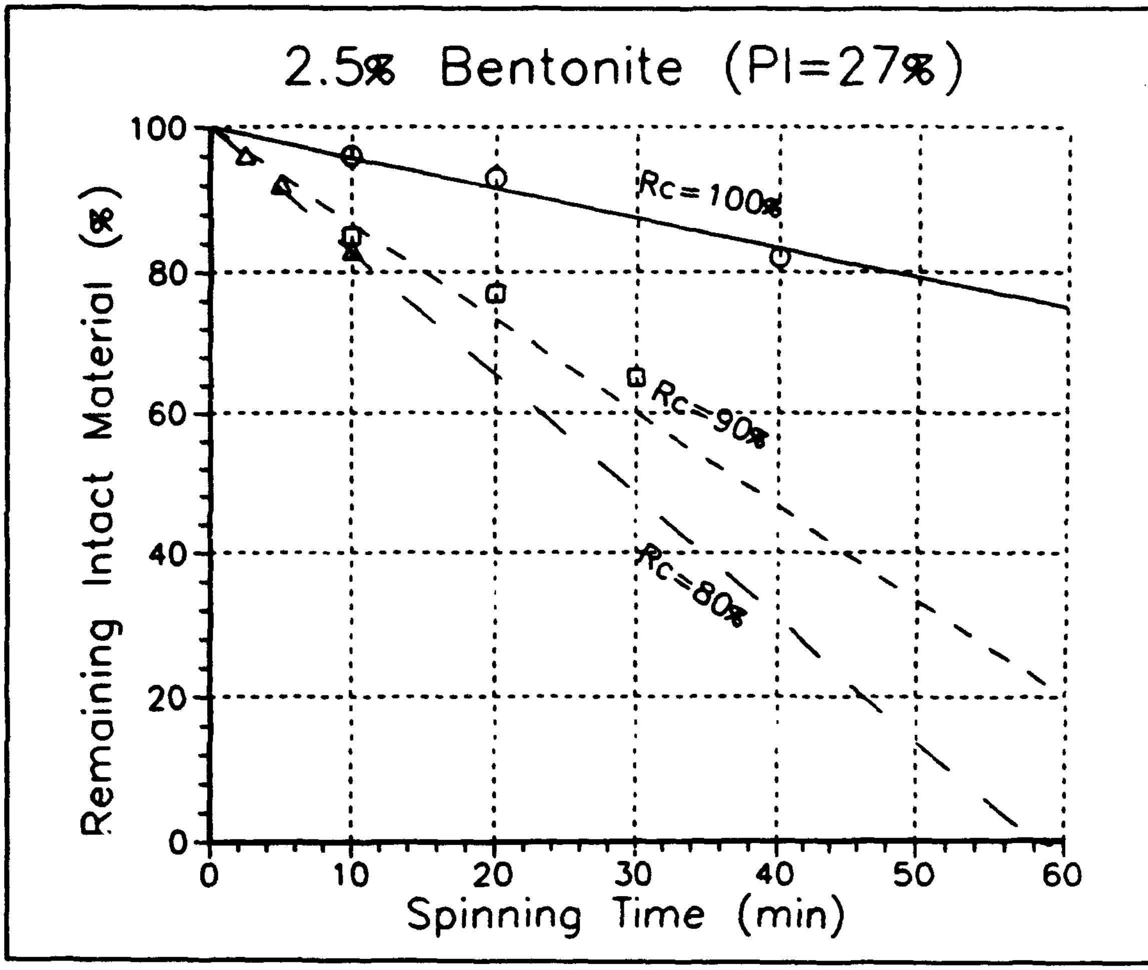


Figure 27. Spin test ($V = 1$ ft/sec, PI = 27 percent)

c. Materials with lower PI degraded significantly more rapidly than material with high PI.

d. Material with lower compaction degraded somewhat more rapidly than material with higher compaction.

e. Higher relative velocities in all three types of tests caused more rapid degradation.

f. More turbulent conditions caused more rapid degradation.

g. Abrasive conditions cause more rapid degradation.

All of these items must be accounted for in order to predict degradation rate. This is discussed in Chapter 5.

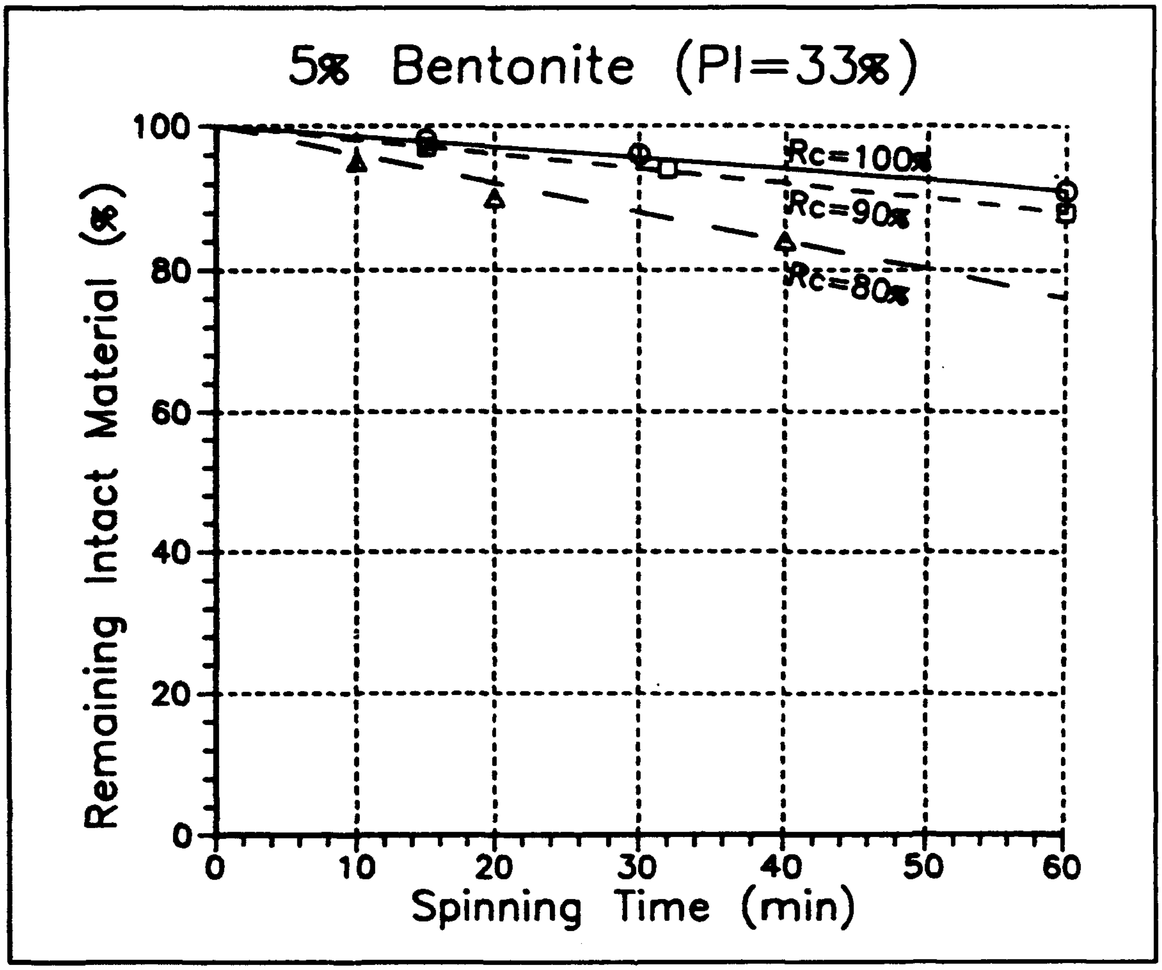


Figure 28. Spin test (V = 1 ft/sec, PI = 33 percent)

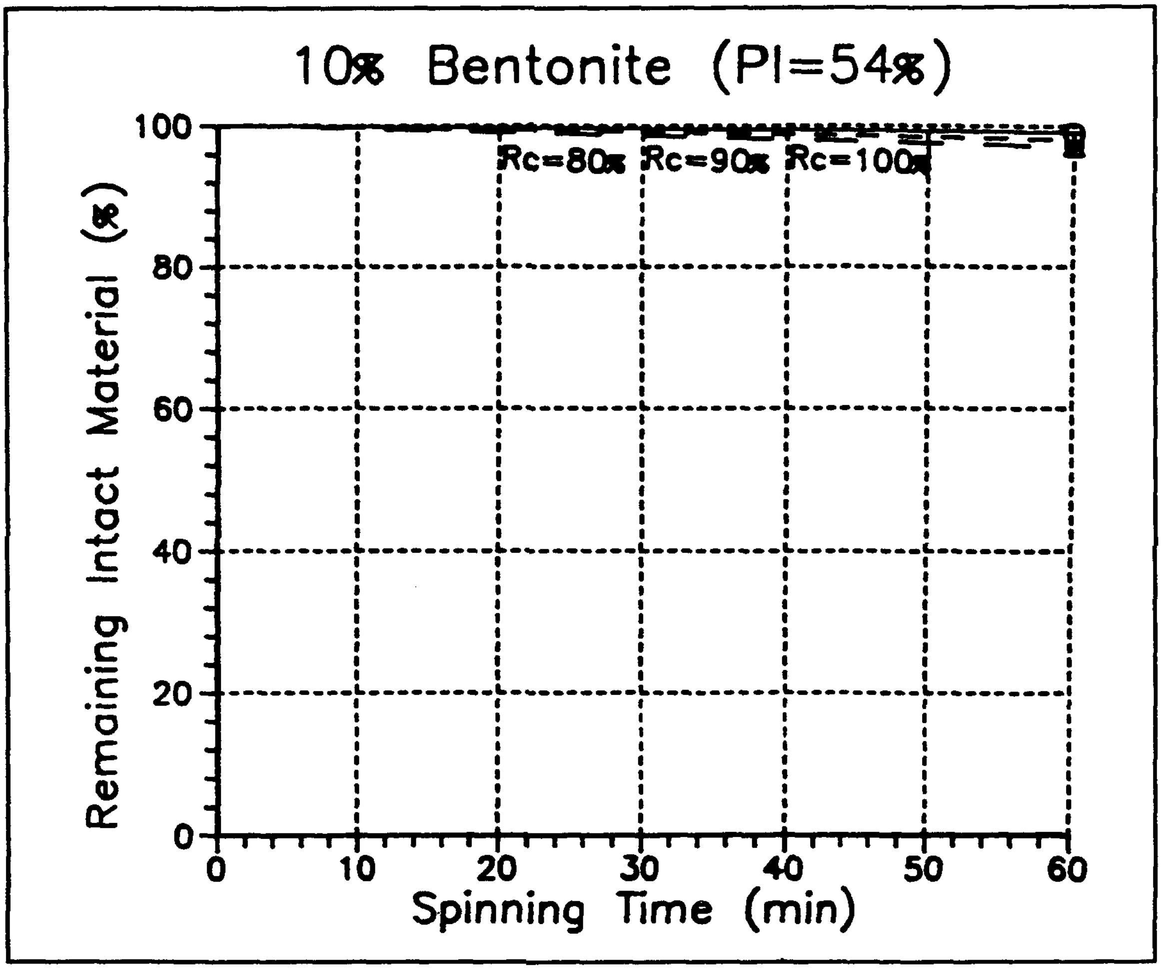


Figure 29. Spin test (V = 1 ft/sec, PI = 54 percent)

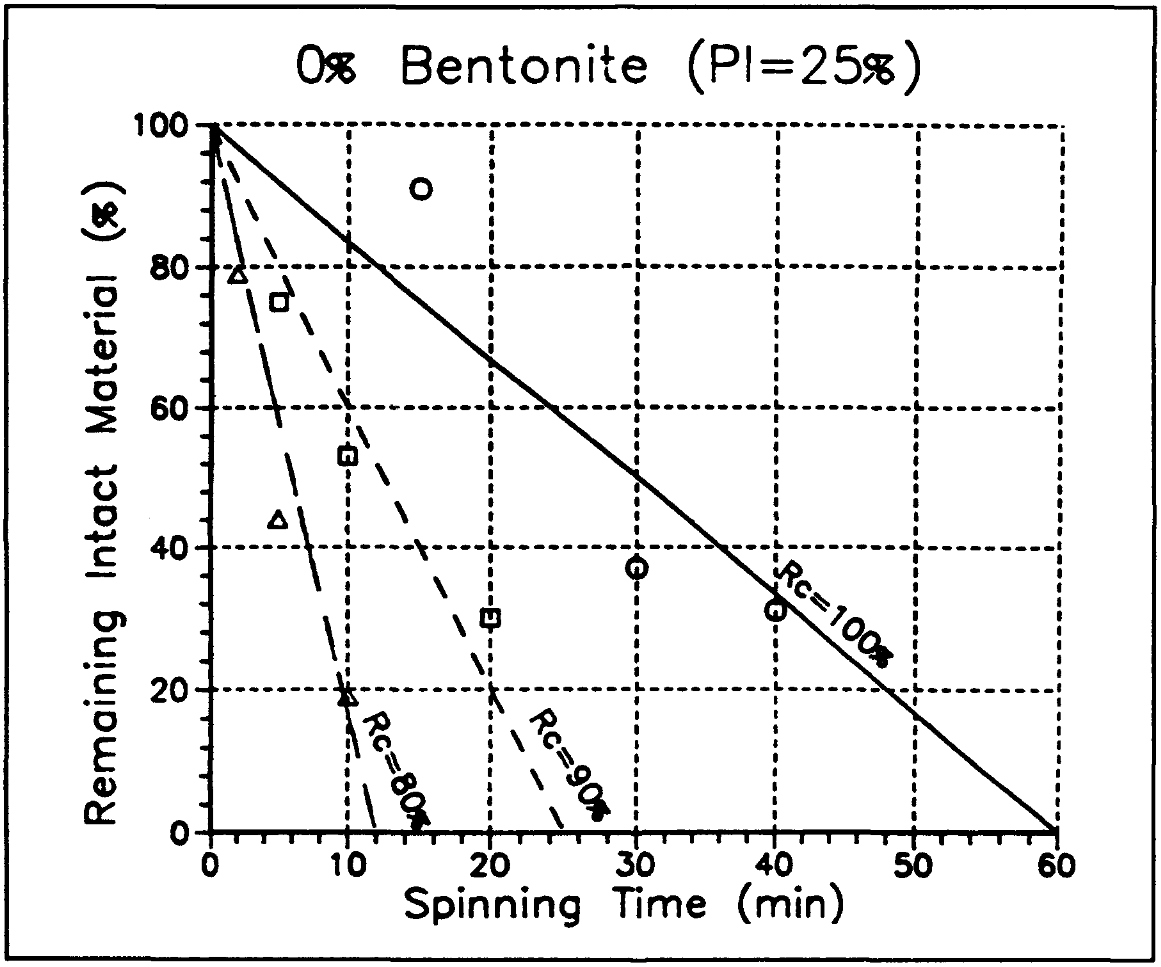


Figure 30. Spin test (*V* = 2.4 ft/sec, PI = 25 percent)

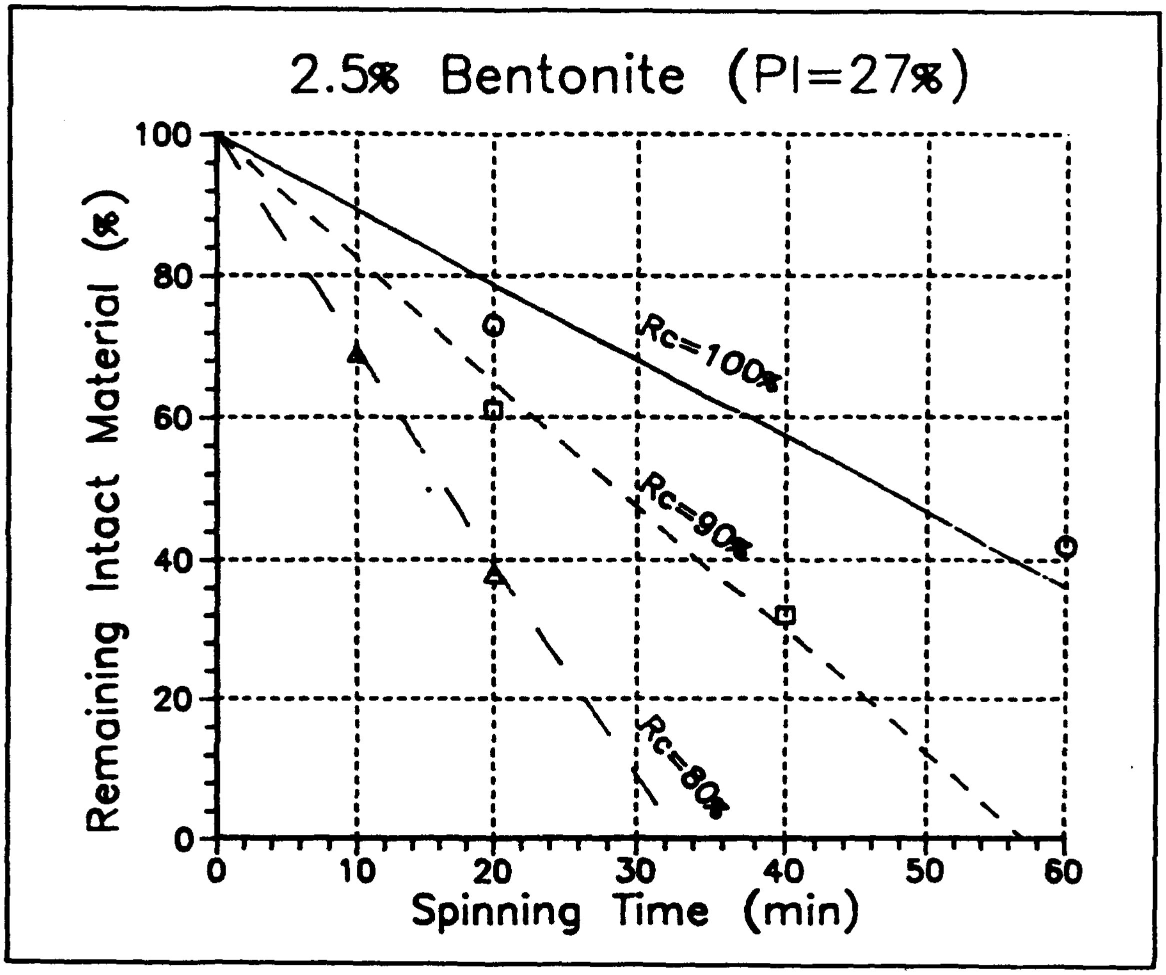


Figure 31. Spin test (V = 2.4 ft/sec, PI = 27 percent)

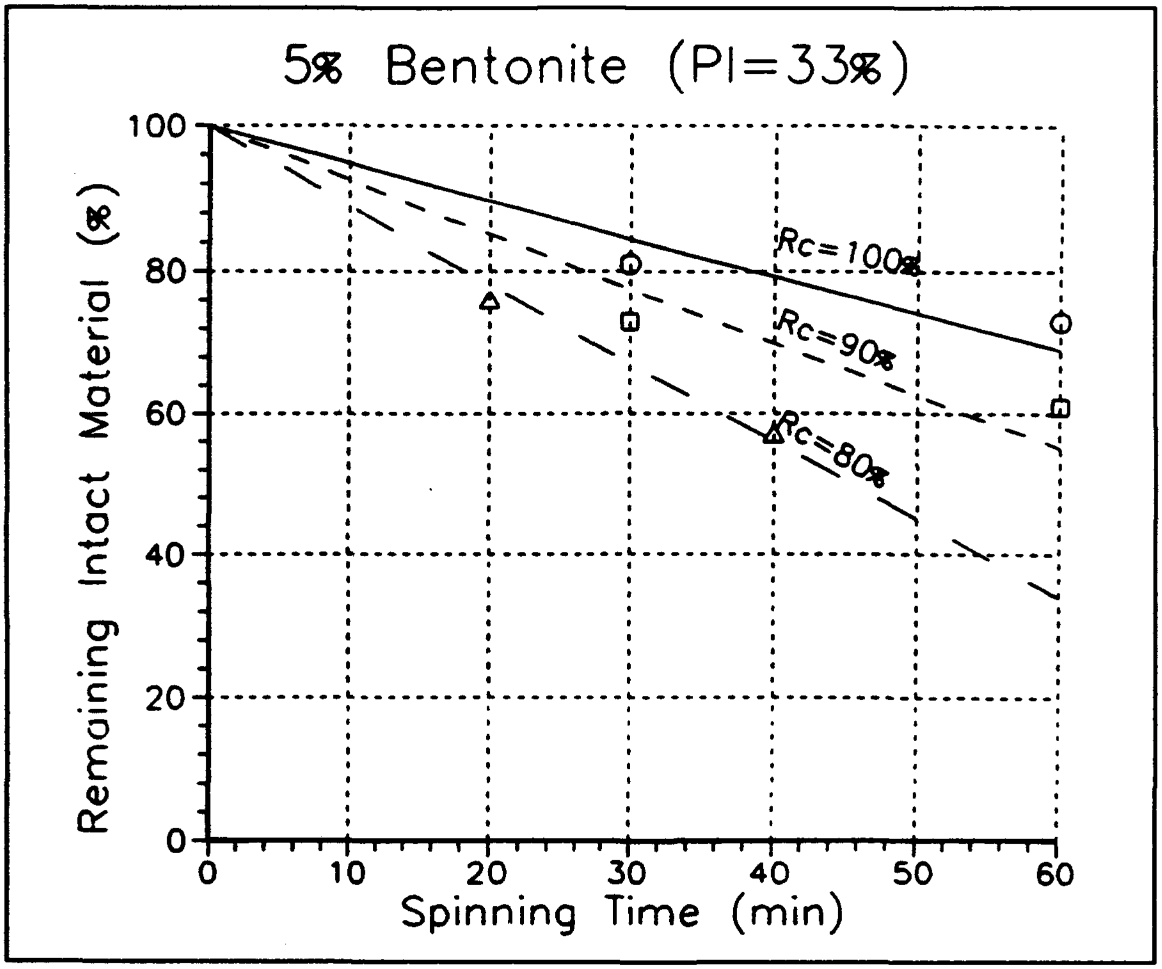


Figure 32. Spin test (V = 2.4 ft/sec, PI = 33 percent)

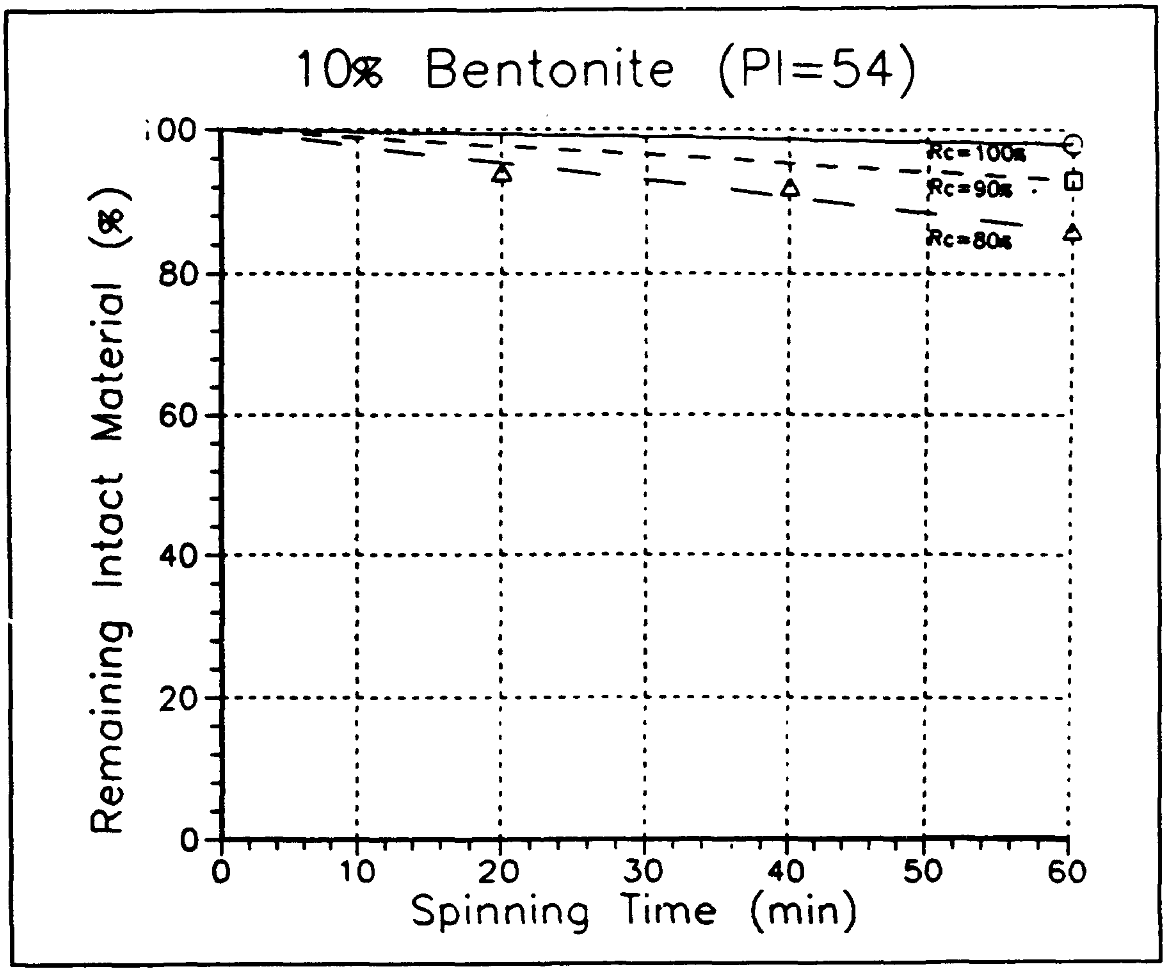


Figure 33. Spin test (V = 2.4 ft/sec, PI = 54 percent)

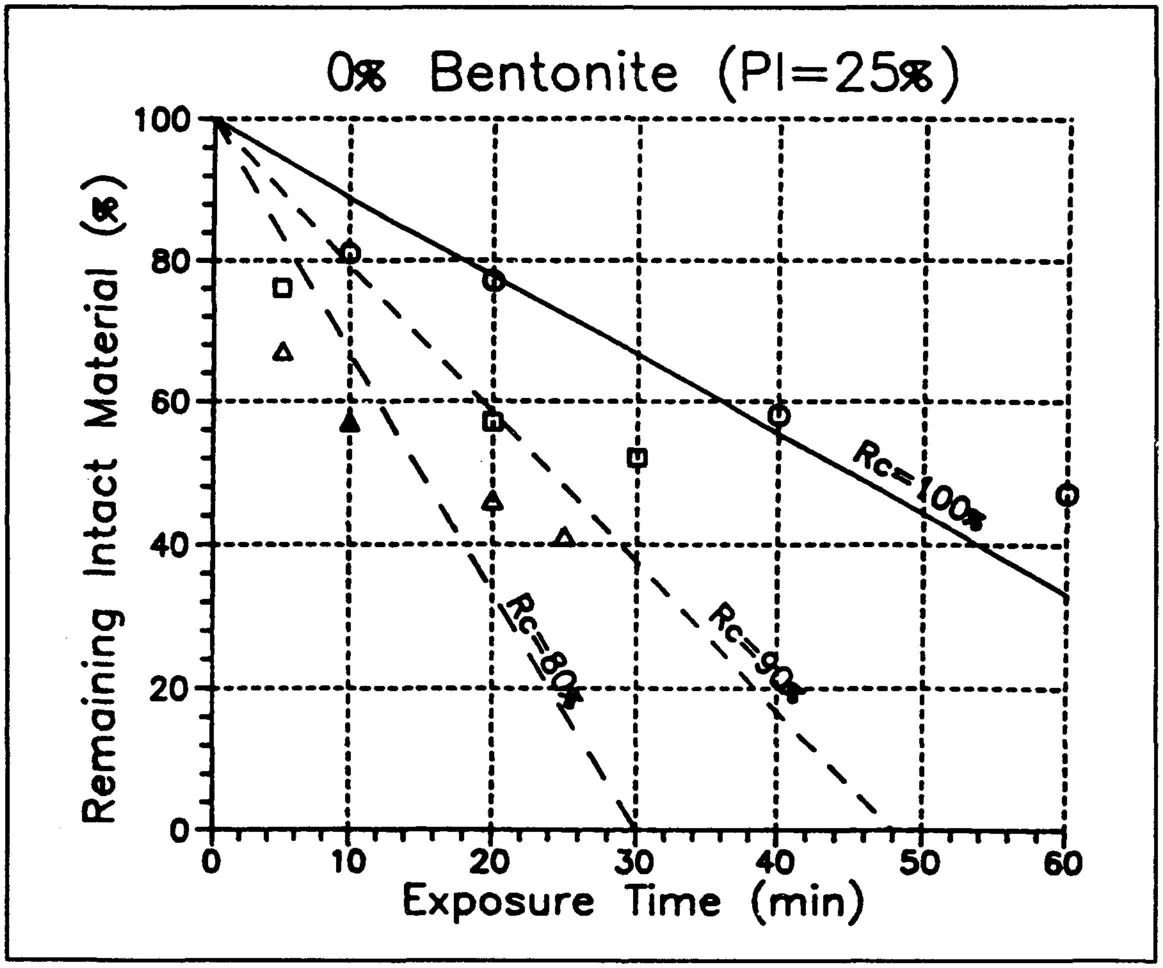


Figure 34. Smooth drum test (V = 2.5 ft/sec, PI = 25 percent)

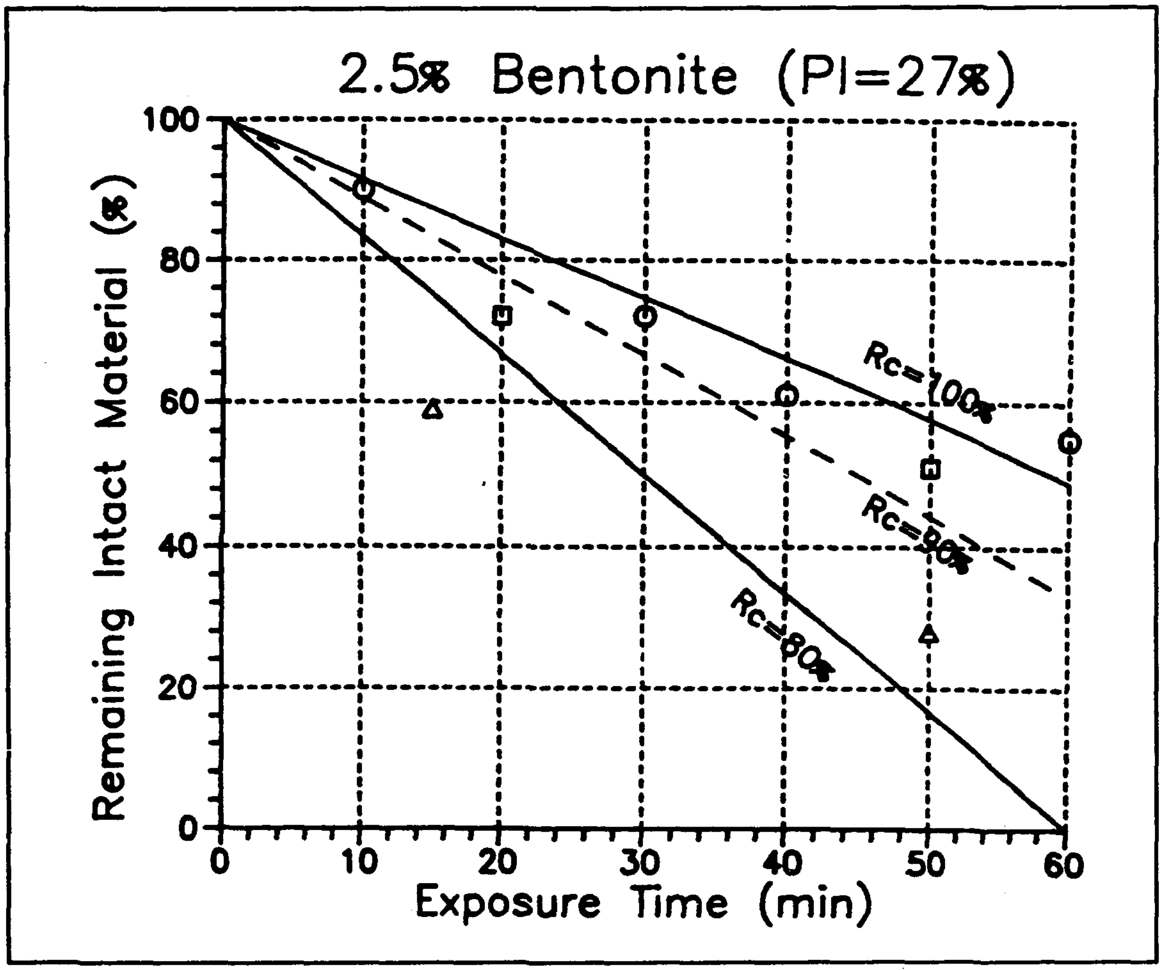


Figure 35. Smooth drum test (V = 2.5 ft/sec, PI = 27 percent)

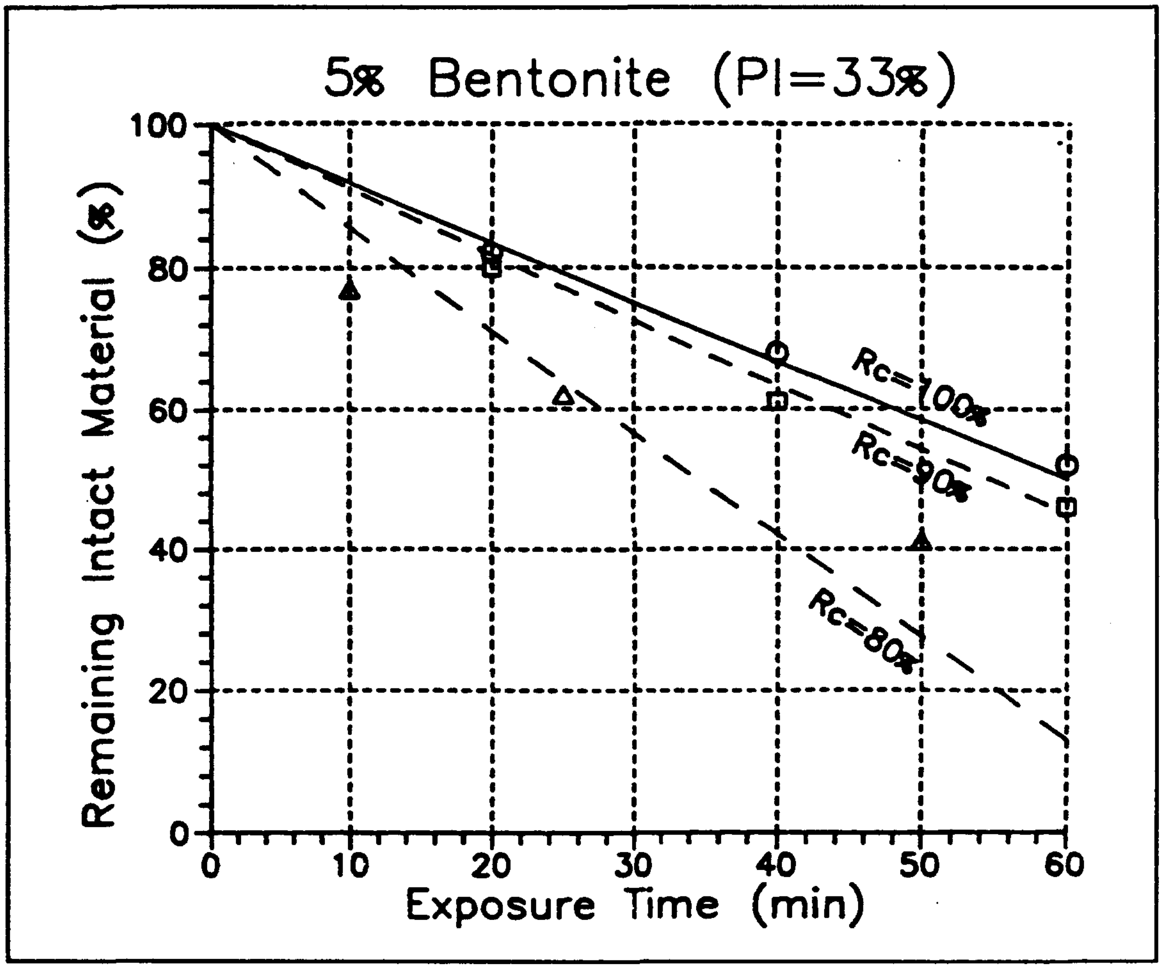


Figure 36. Smooth drum test (V = 2.5 ft/sec, PI = 33 percent)

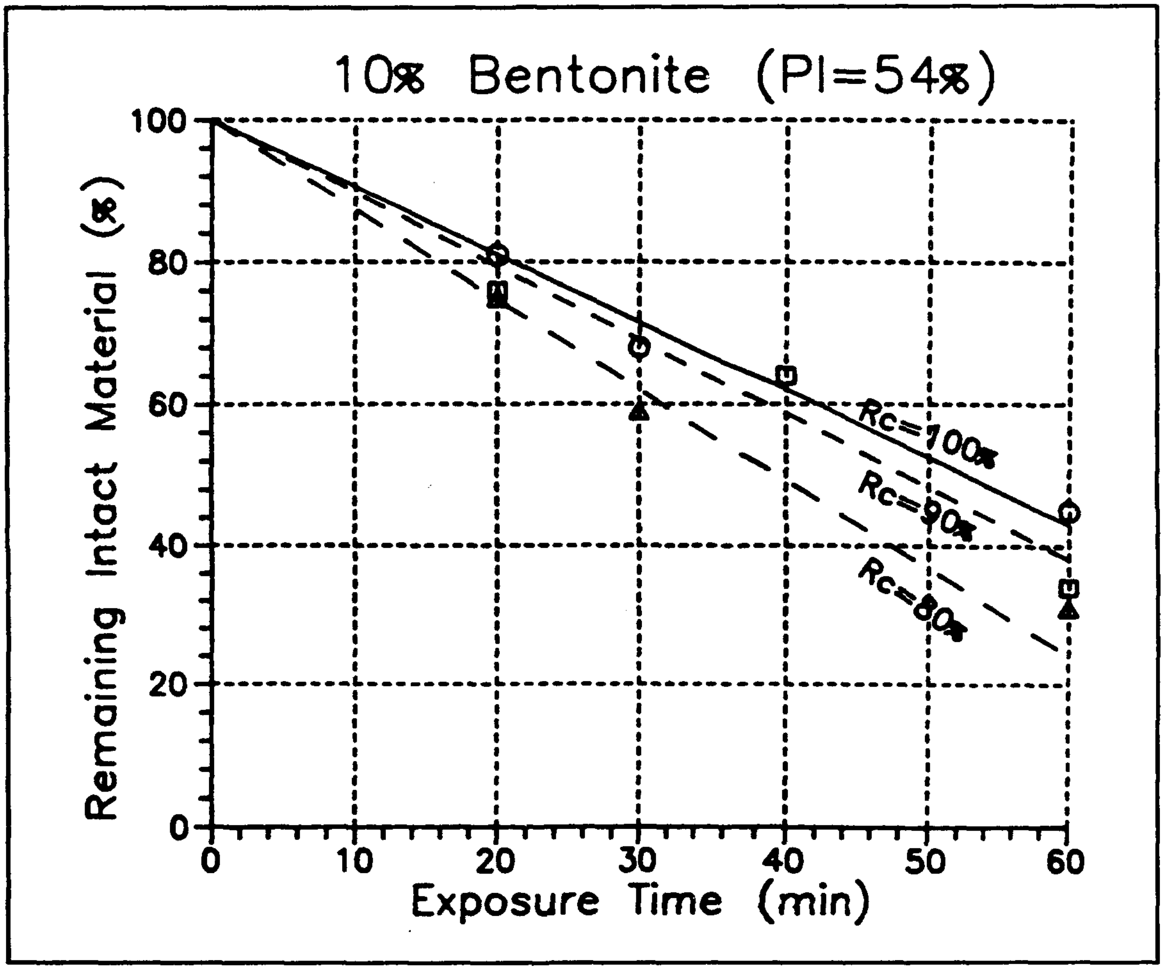


Figure 37. Smooth drum test (V = 2.5 ft/sec, PI = 54 percent)

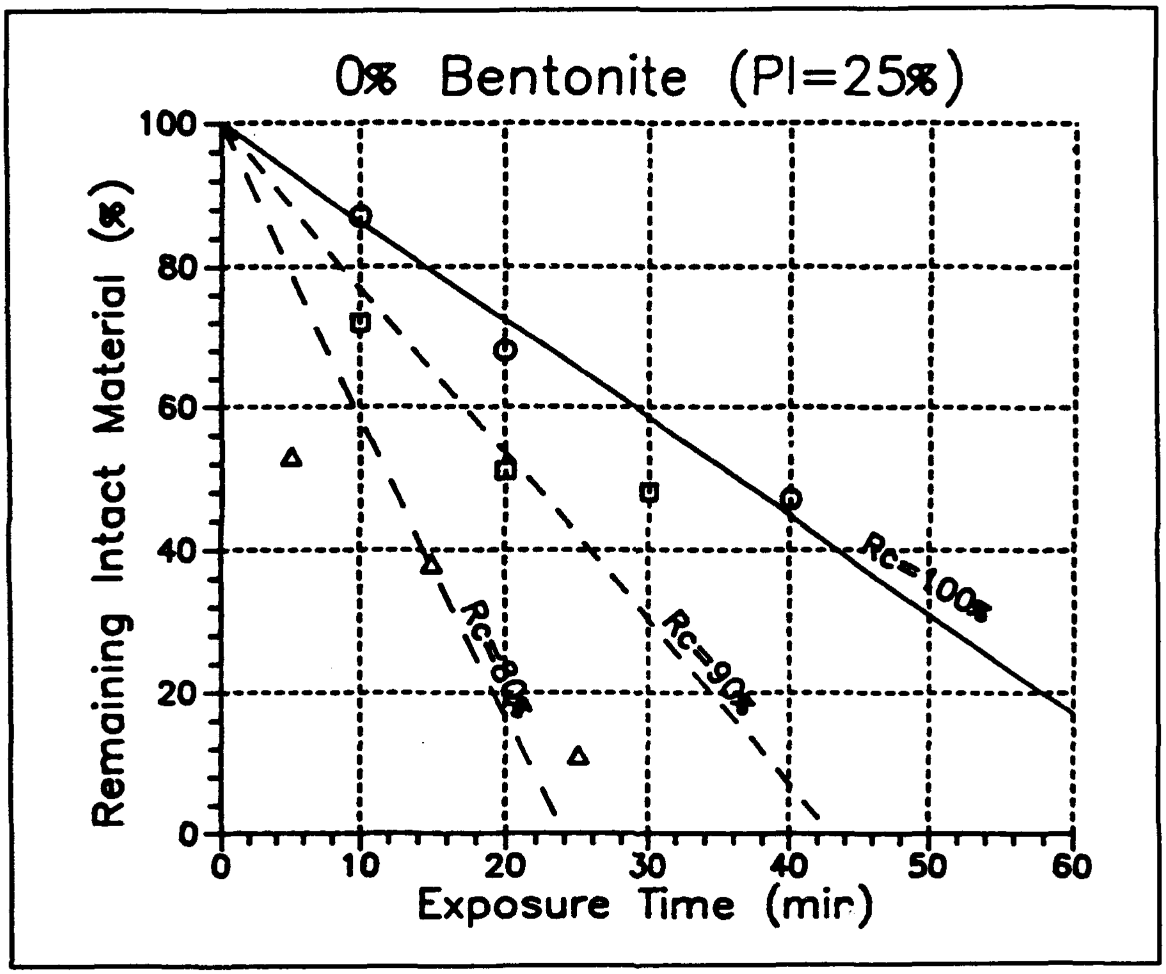


Figure 38. Rough drum test (V = 2.5 ft/sec, PI = 25 percent)

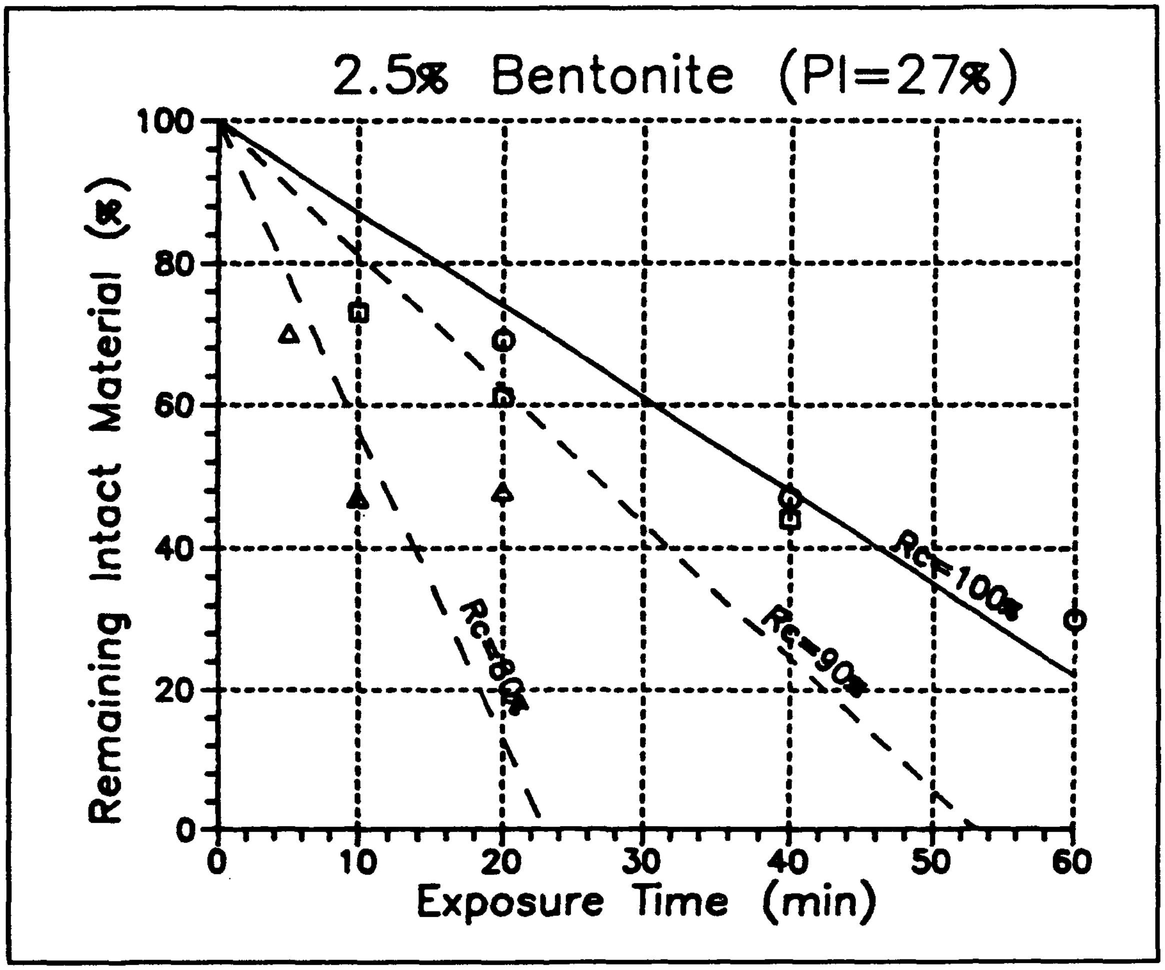


Figure 39. Rough drum test (V = 2.5 ft/sec, PI = 27 percent)

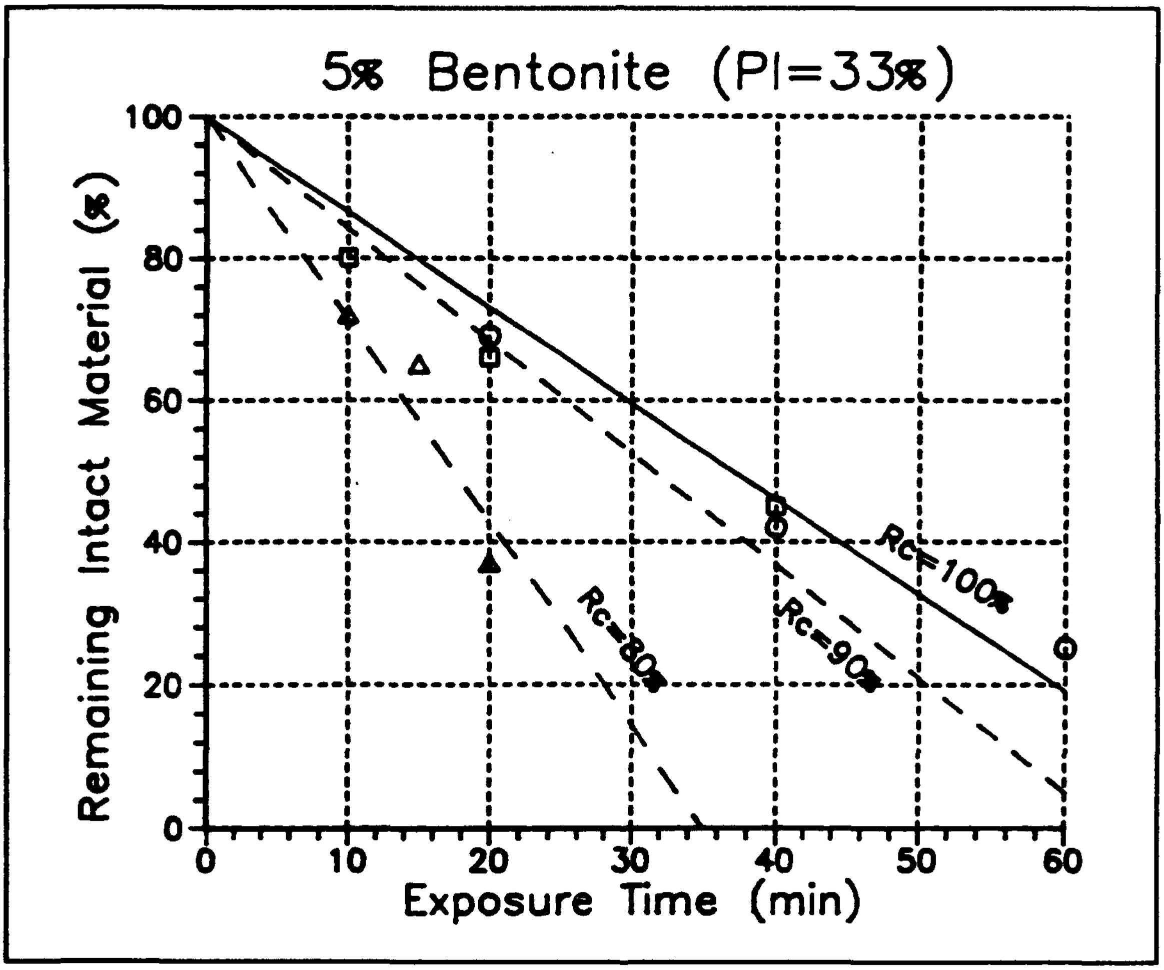


Figure 40. Rough drum test (V = 2.5 ft/sec, PI = 33 percent)

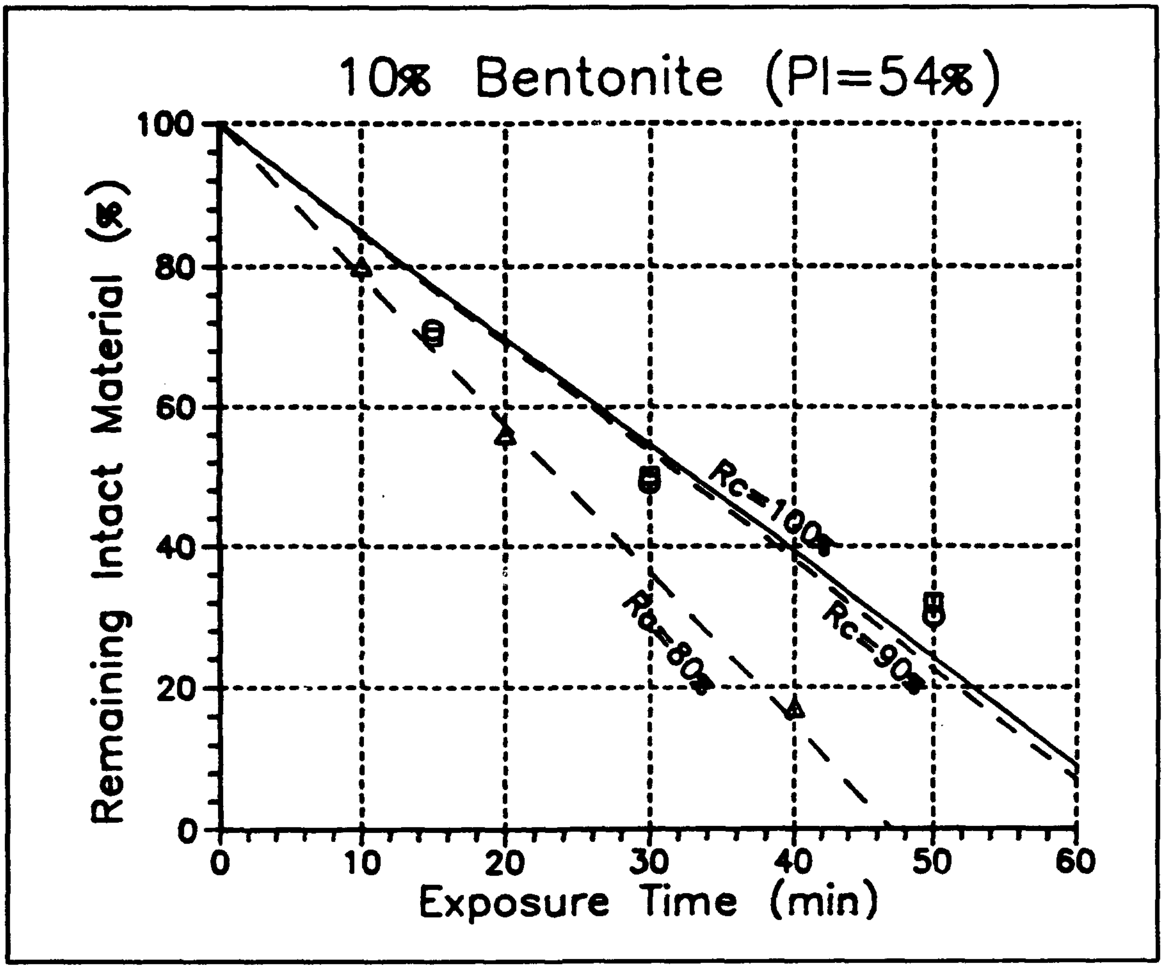


Figure 41. Rough drum test (*V* = 2.5 ft/sec, PI = 54 percent)

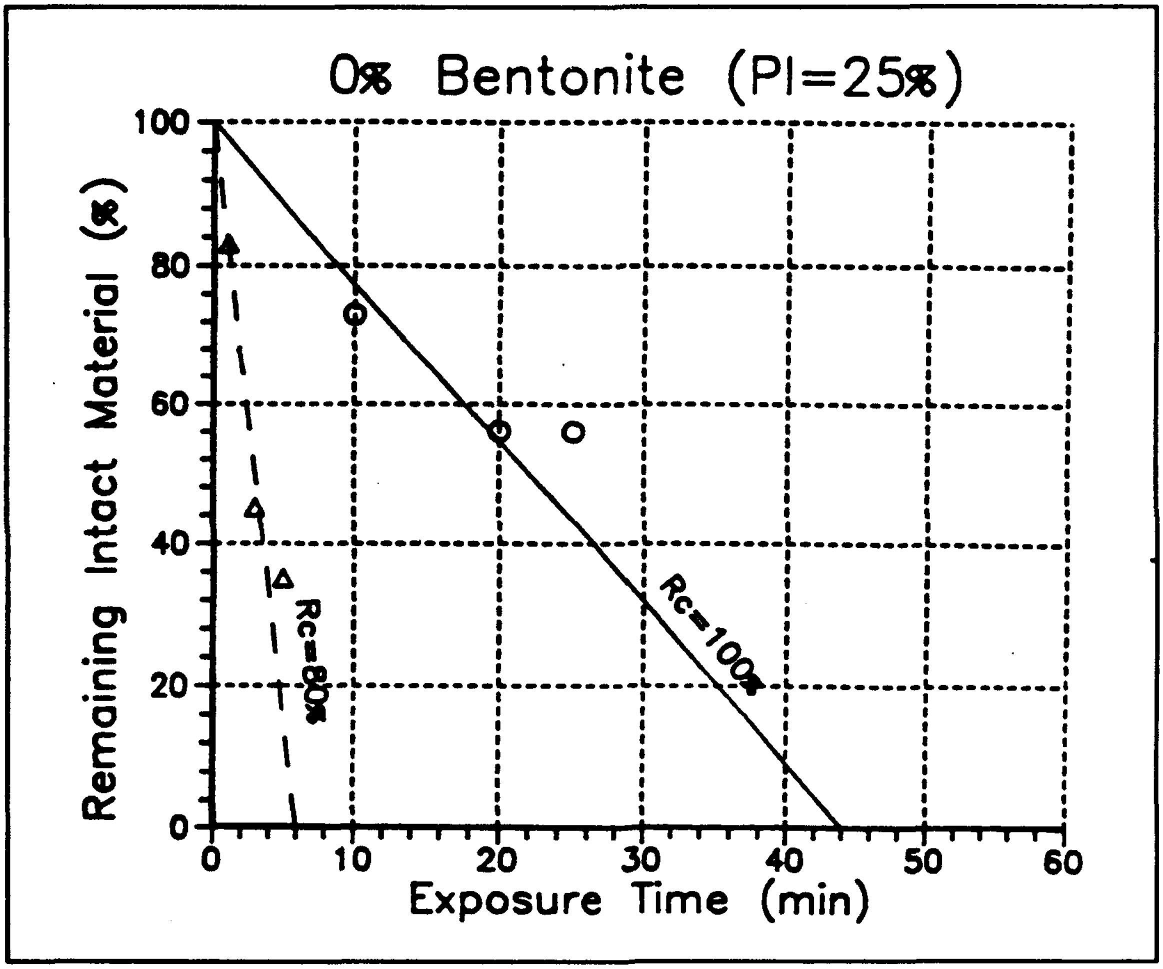


Figure 42. Rough drum test (V = 5 ft/sec, PI = 25 percent)

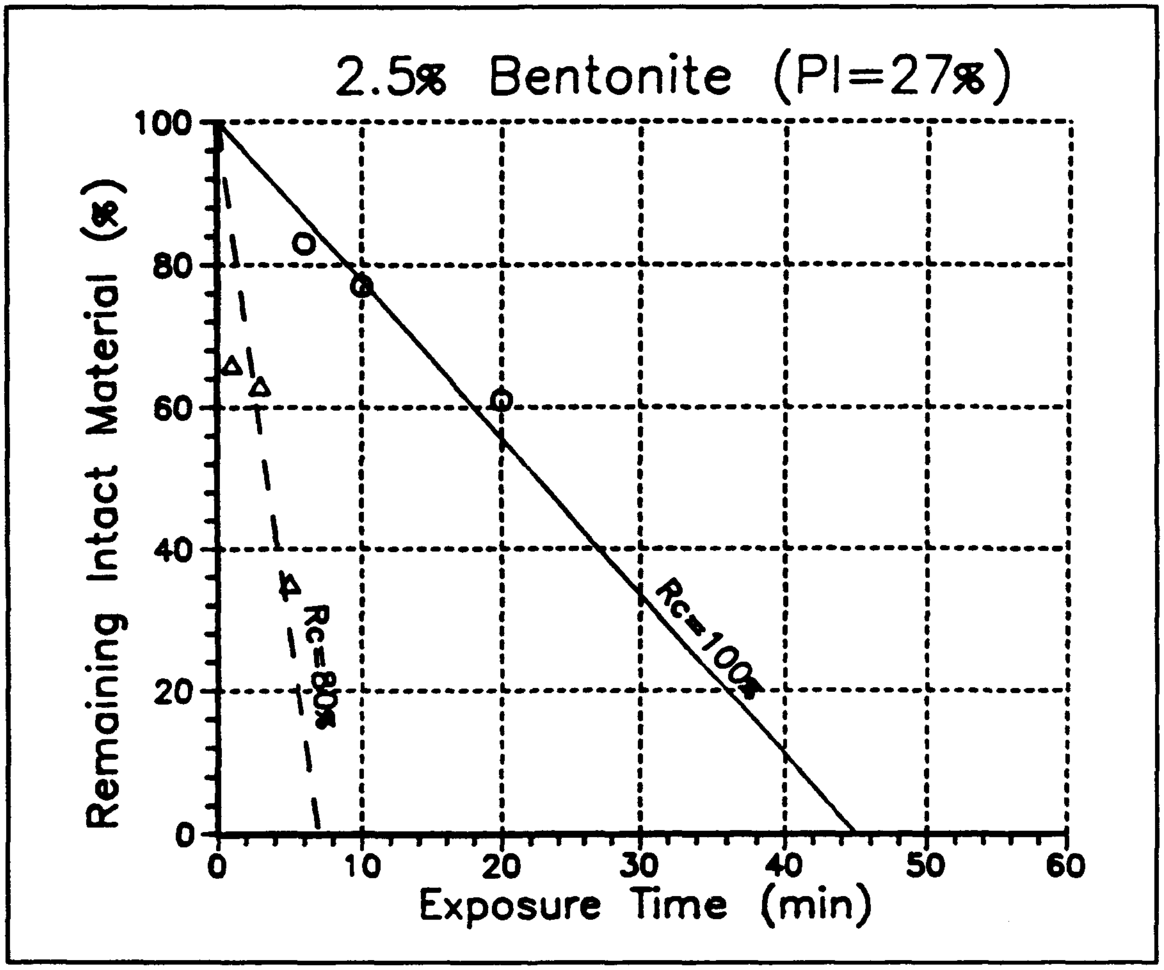


Figure 43. Rough drum test (V = 5 ft/sec, PI = 27 percent)

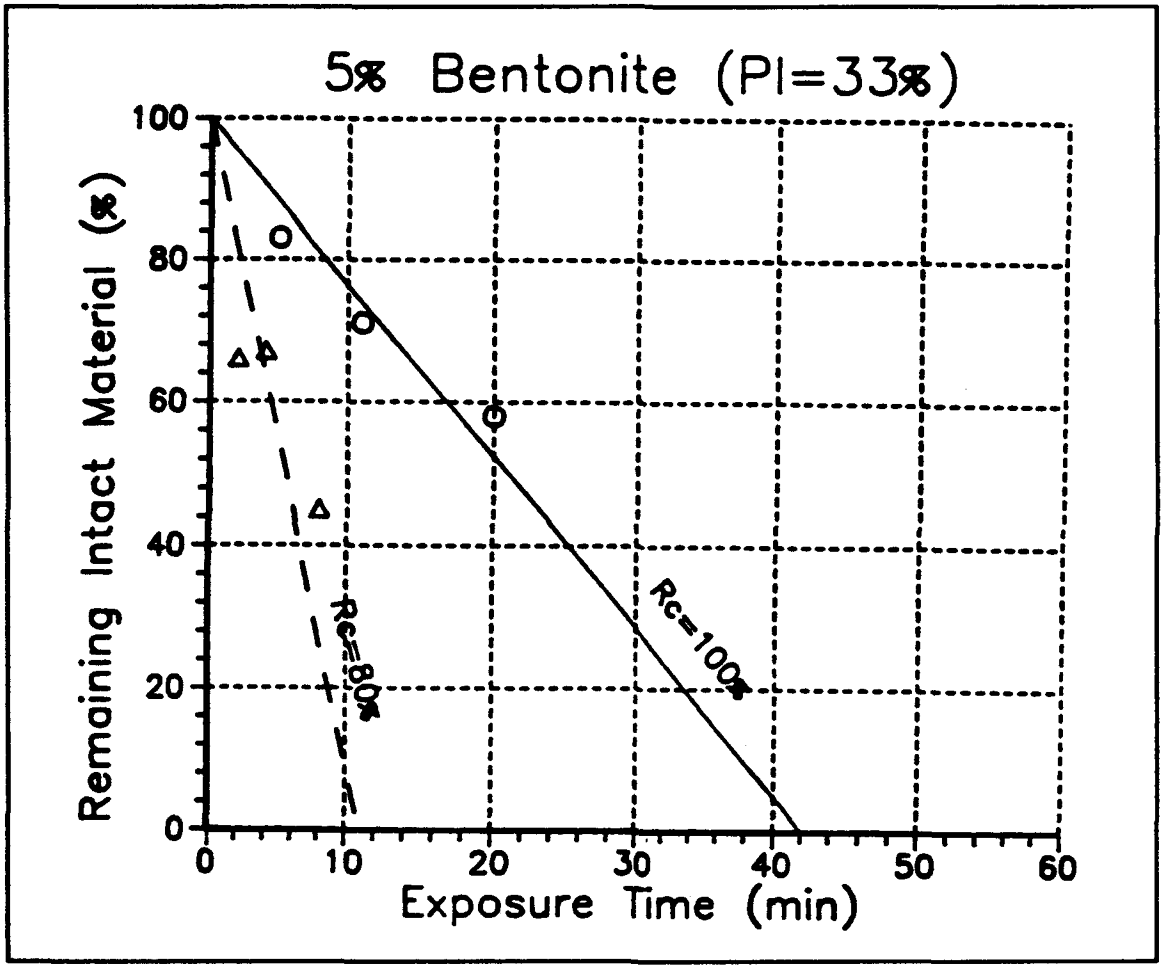


Figure 44. Rough drum test ($V = 5$ ft/sec, PI = 33 percent)

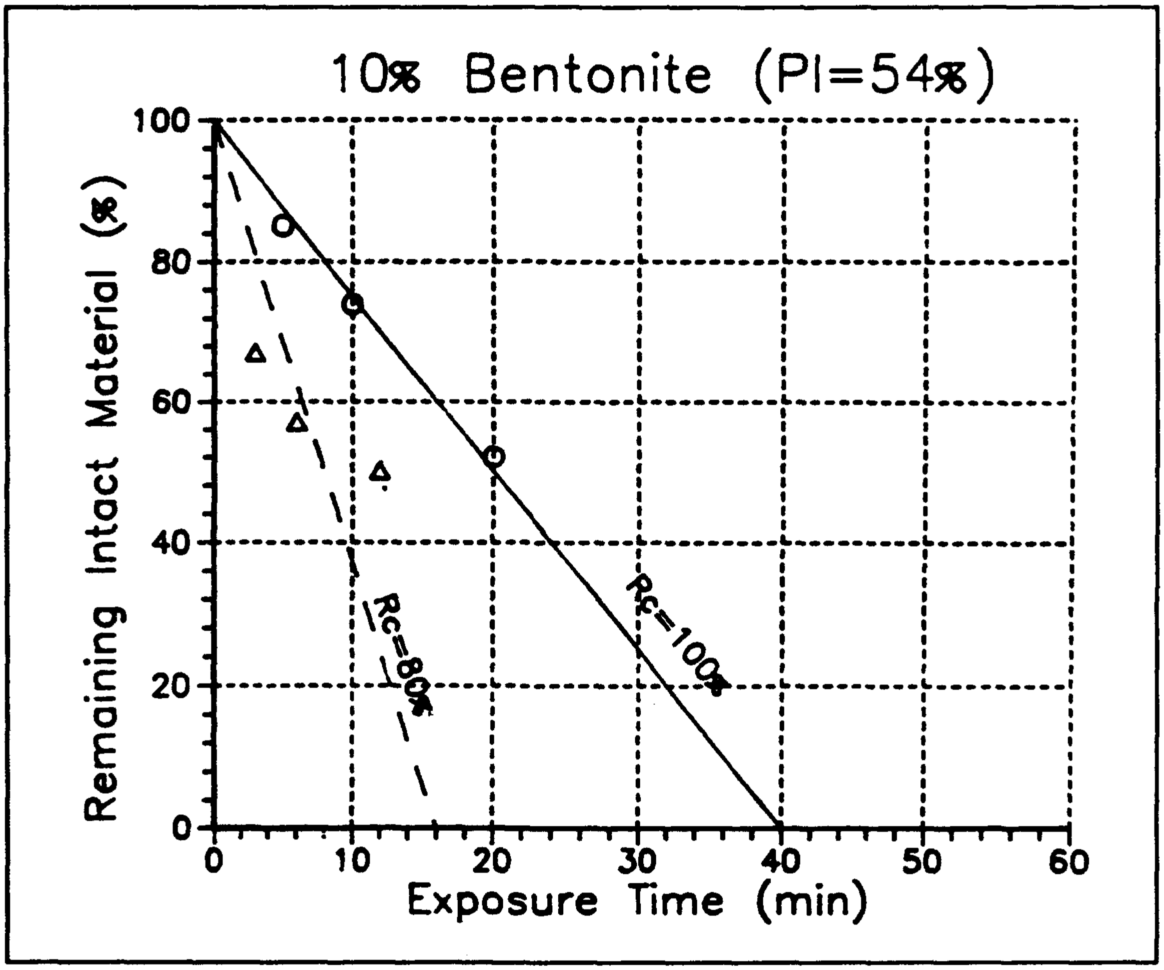


Figure 45. Rough drum test (V = 5 ft/sec, PI = 54 percent)

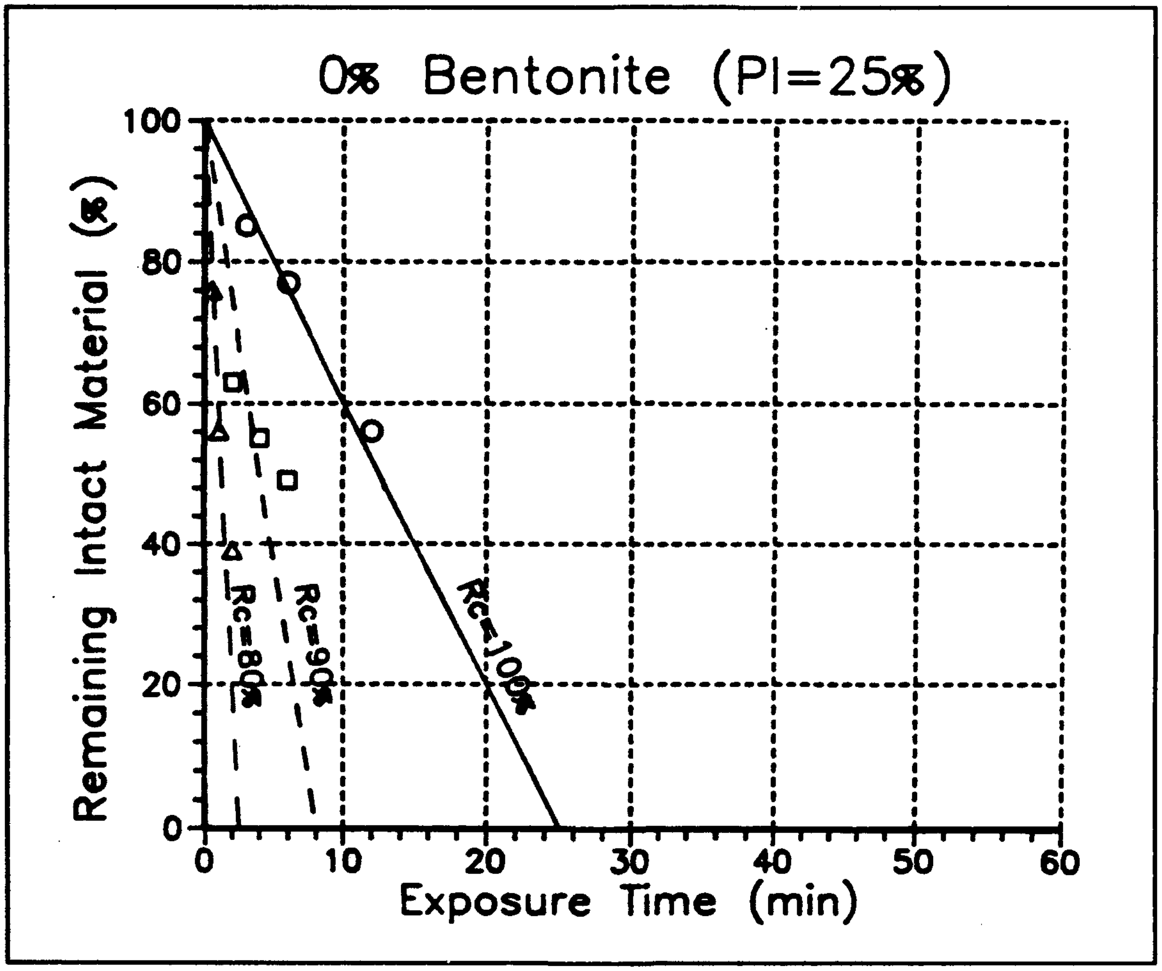


Figure 46. Rough drum test (V = 7.5 ft/sec, PI = 25 percent)

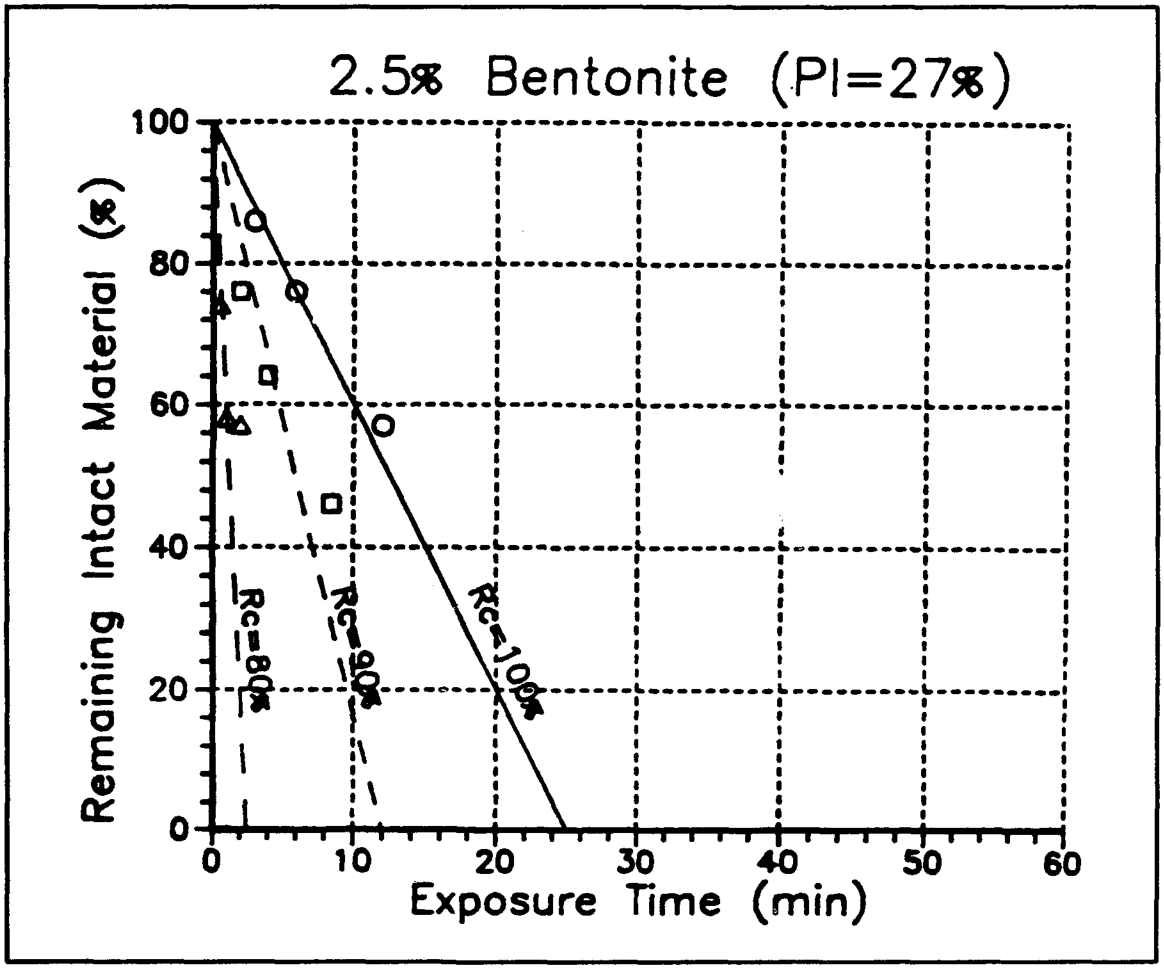


Figure 47. Rough drum test (V = 7.5 ft/sec, PI = 27 percent)

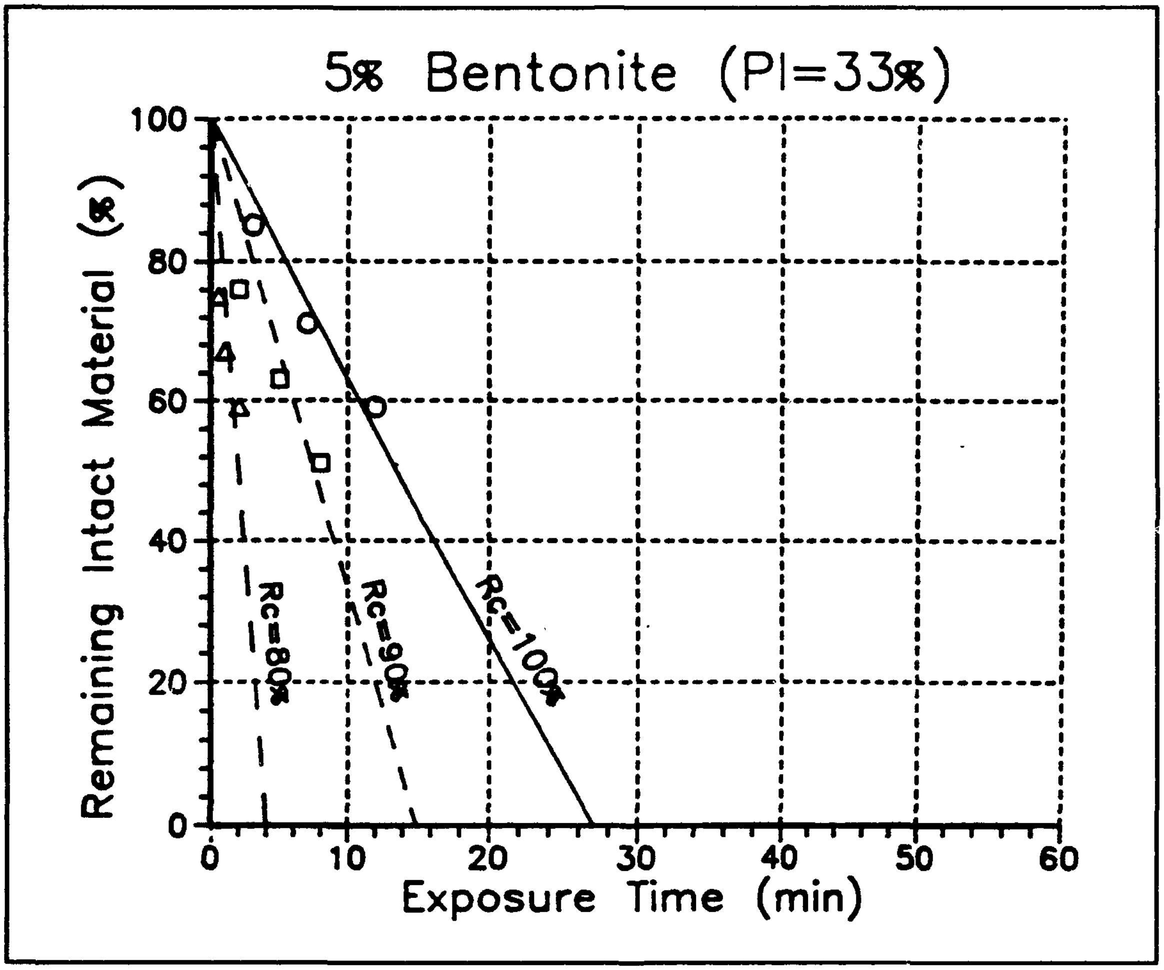


Figure 48. Rough drum test ($V = 7.5$ ft/sec, PI = 33 percent)

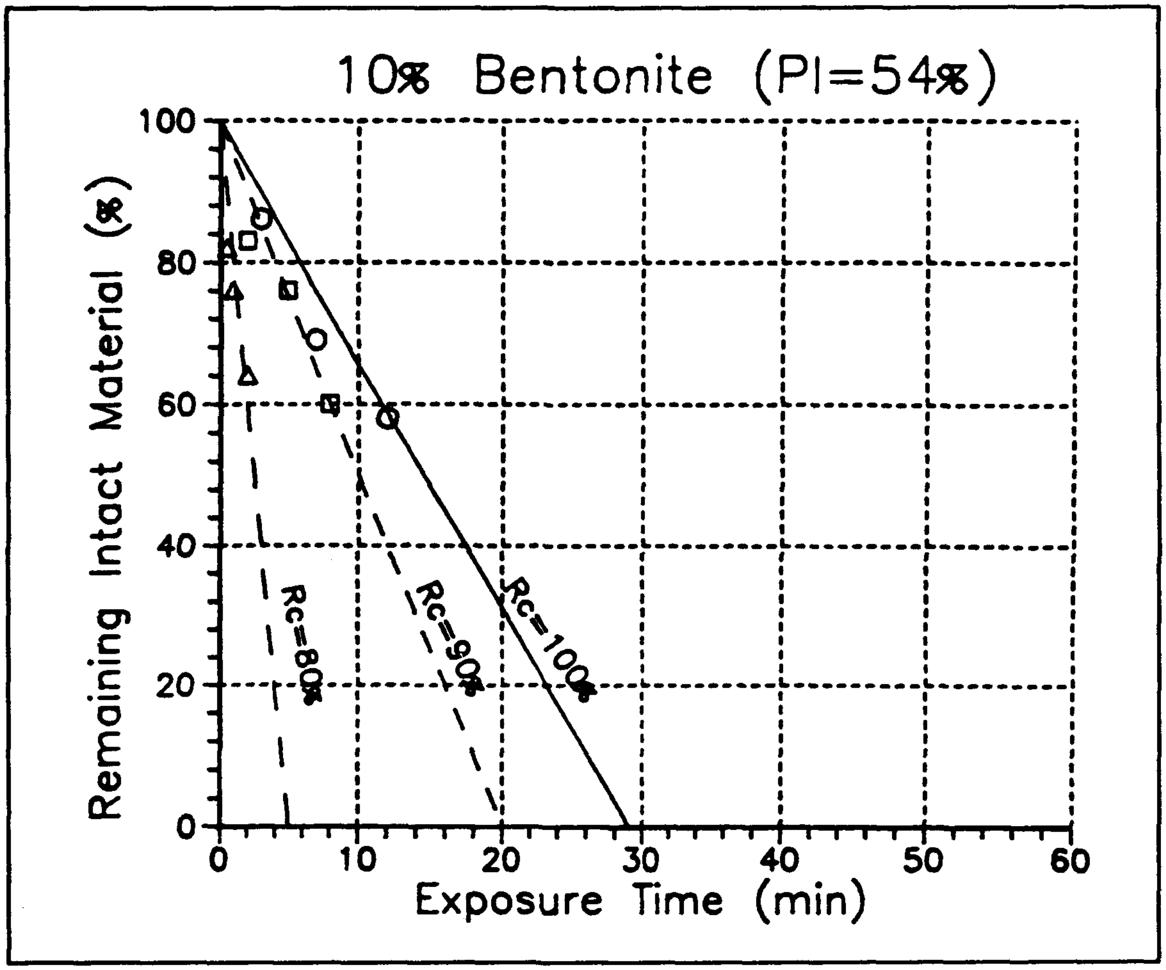


Figure 49. Rough drum test (V = 7.5 ft/sec, PI = 54 percent)

5 Interpretation of Test Results

Predicting Dredged Clay Behavior

The presented test results show rates of clay lump degradation for different material properties and under various exposure conditions. The material properties examined were selected to simulate the wide range of possible clays that might be encountered on dredging projects. The various exposure conditions imposed on the clay lumps were designed to resemble the hydraulic transport process involved in dredging.

As stated in Chapter 3, the hydraulic transport process imposes forces upon clay lumps that may cause lump degradation, or conversely, clay balling to occur. Predictions regarding the tendency for degradation or clay balling are important to both the engineer and the dredging contractor. This part of the report will refine the experimental data presented to a point where the factors involved in clay balling can be better appreciated and reasonable predictions of lump degradation can be made.

Importance to the engineer

Prediction of dredged material behavior during transport is important to the engineer for a number of reasons. First, the engineer may require fill materials near dredging sites that are suitable for construction. These materials may be needed for projects such as flood control dikes along a waterway or containment dikes. Using dredged material may be an economical means of acquiring fill materials for construction, if it can function properly. How material will behave at the end of the dredge line, after being transported hydraulically, is related to the in situ material properties and to the material's handling during the dredging process. If dredged material is selected for use in construction, the engineer may want to specify certain handling requirements during the dredging and transport process (e.g., cutting size, transport velocity, etc.) to ensure the material's suitability at the end of the dredge line. Secondly, a material that is highly friable will slurrify after it has been dredged and transported. In this case, the engineer must ensure that adequate containment is

provided for this type of material or it may immediately flow back into the waterway. Third, in the bid process the material to be dredged must be described accurately. That is, if the material is classified as friable but in reality it tends to maintain its lumpy shape, the dredging process might be more expensive by an order of magnitude. The end result is a costly dispute typically resolved in court. Adequate specifications in the bid, using simple material parameters, should eliminate such disputes and facilitate work.

Importance to the dredging contractor

From the dredging contractor's perspective, the material's behavior is also important. The dredging contractor needs answers to the following questions: How easily can the material be cut by the cutterhead?; Will the material ball into large clods that can clog the pipe and pump?; Will the material slurrify rapidly, thereby making it easier to pump?; Will the material be discharged as large clods that quickly pile up under the discharge point, and therefore must be constantly pushed away to keep the area clear?; If the dredge materials must be transported by barge, will the material have to be transported with a large amount of water or will the solids quickly settle out?; When the material is discharged from the barge will it be so sticky that the barge must be mechanically scraped in order to discharge the material? With reliable material descriptions, the dredging contractor can address these issues to better plan and price the project.

Refinement of Experimental Results

The experimental results from Chapter 4 have been replotted in a variety of graphical presentations. This will allow further insight into the factors involved in the degradation rate of clays. Four different sets of graphs will next be introduced that were prepared to interpret the relative effect of the factors involved, and assist in making predictions on the behavior of dredged clay material. Because the spin and drum tests are designed to measure degradation caused by different hydraulic effects, a brief explanation of each test will be given next before proceeding with results and interpretations.

Relevance of spin and drum test results

The purpose of the spin test is to isolate the effect of a difference in velocity between the transport fluid and the material it is dragging (i.e., hydraulic transport). The velocities chosen for use were such as to closely resemble the typical difference in velocity between the transport fluid and the clay lumps in a dredge line.

The purpose of the drum test was to model the following factors causing lump degradation: the difference in relative velocities between the fluid and the lumps; flow turbulence; and clay lumps colliding with the pipe wall. The degradation effects due to these forces in the drum test simulated the

mechanisms causing lump degradation in a dredge line. It should be noted that the velocities used in the drum test may appear low compared with actual dredge line velocities (i.e., velocities used in the drum test were between 2.5 to 7.5 ft/sec whereas actual dredge line velocities for sands range from 5 to 25 ft/sec (Turner 1984). Actual dredge line velocities, however, represent an average fluid flow within the pipe, with high velocity near the center and low velocity near the pipe wall. Since the majority of clay material is typically dragged near the bottom of the pipe, the velocities used in the drum test are believed to adequately model reality. Furthermore, average velocities of fluid containing clay lumps are lower, possibly by an order of magnitude, as compared with a sandy mixture. Thus, the velocity range chosen seems appropriate.

Rate of lump degradation versus plasticity index as a function of relative compaction

Figures 50 through 55 show rate of lump degradation versus plasticity index as a function of relative compaction. Graphs have been prepared for each velocity used in the spin, smooth drum, and rough drum test. These graphs were generated using the slopes of degradation versus elapsed time lines in the figures from Chapter 4. These slopes represent rate of lump degradation. The various rates of degradation found for the different plasticities tested were then fit by a cubic spline. The cubic spline represents a best fit, smooth curve through the tested plasticities, giving an approximation of the expected rate of degradation for materials from PI = 25 percent to PI = 54 percent. The figures clearly show the change in rate of degradation as a function of relative compaction and plasticity index. It can be seen that lower compaction and lower plasticity index result in more rapid degradation.

Rate of lump degradation versus tangential velocity as a function of relative compaction

The second set of figures (Figures 56 through 67) shows rate of lump degradation versus tangential velocity *V* as a function of relative compaction. The graphs are useful because the effect of compaction on rate of degradation for a given PI is apparent. The effect of velocity can also be observed. The procedure for constructing these figures was as follows. From results presented in Chapter 4, the rate of degradation for a chosen test velocity was determined at a certain plasticity. Next, the degradation rate for the same material tested at a higher velocity was determined. The different degradation rates were then plotted versus their corresponding velocities as shown.

The figures show that increased velocity greatly increases degradation in lightly compacted material but only slightly increases degradation in heavily compacted material. Examining this set of figures as a group, one sees that the rate of degradation for lightly compacted material decreases as plasticity increases. Also, the change in rate of degradation for highly compacted material is very small regardless of the plasticity used in the experiments.

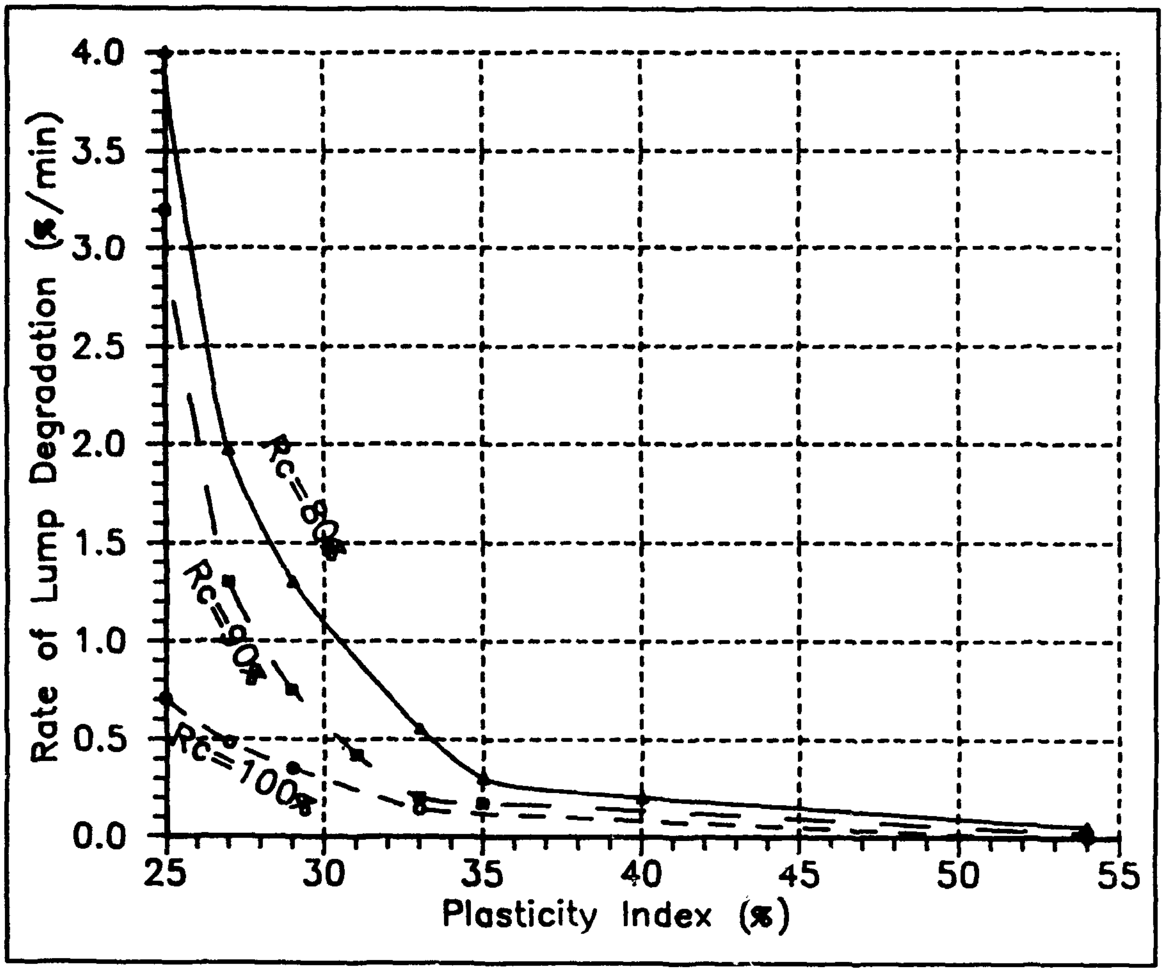


Figure 50. Rate of lump degradation versus PI for spin test at $V = 1$ ft/sec

Since only two velocities were used in the spin test, a straight line was chosen to estimate the change in rate of degradation. However, in the drum test, three velocities were tested, revealing a nonlinear trend in the rate of degradation with increased velocity.

Rate of lump degradation versus plasticity index as a function of velocity

The third set of graphs (Figures 68 through 73) shows rate of lump degradation versus plasticity index, as a function of velocity. Graphs have been prepared for each compaction level used in the spin and rough drum tests. The data points were taken directly from results presented in the last chapter. From the figures it can be seen that higher velocity and lower plasticity result in increased degradation.

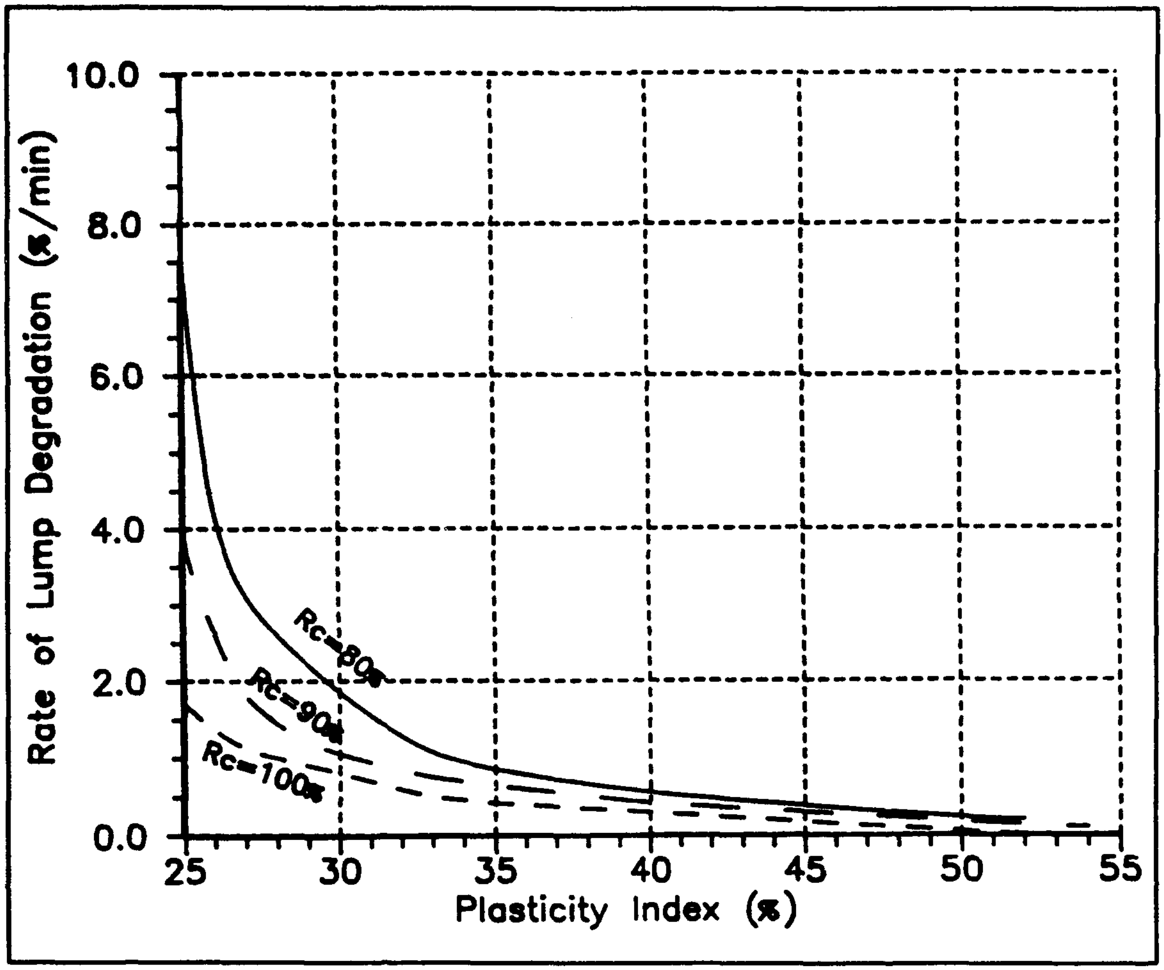


Figure 51. Rate of lump degradation versus PI for spin test at $V = 2.4$ ft/sec

Rate of lump degradation versus tangential velocity as a function of plasticity index

The fourth set of graphs (Figures 74 through 79) shows rate of lump degradation versus tangential velocity, as a function of plasticity index. Each figure is prepared for a specific test and compaction level. These graphs are useful because the effect of plasticity on rate of degradation for a given compaction is apparent. The effect of velocity can also be observed.

The information for drawing these graphs was derived from test results presented in the previous chapter. That is, the rate of degradation at selected plasticities was found for a given test and compaction level. Next, the rate of degradation under the same conditions but at a higher velocity was found. The different degradation rates were then plotted versus their corresponding velocities in Figures 74 through 79. A graph has been prepared for the spin and rough drum tests for each compaction level used. Figures for the smooth drum could not be drawn in this case since only one velocity was tested.

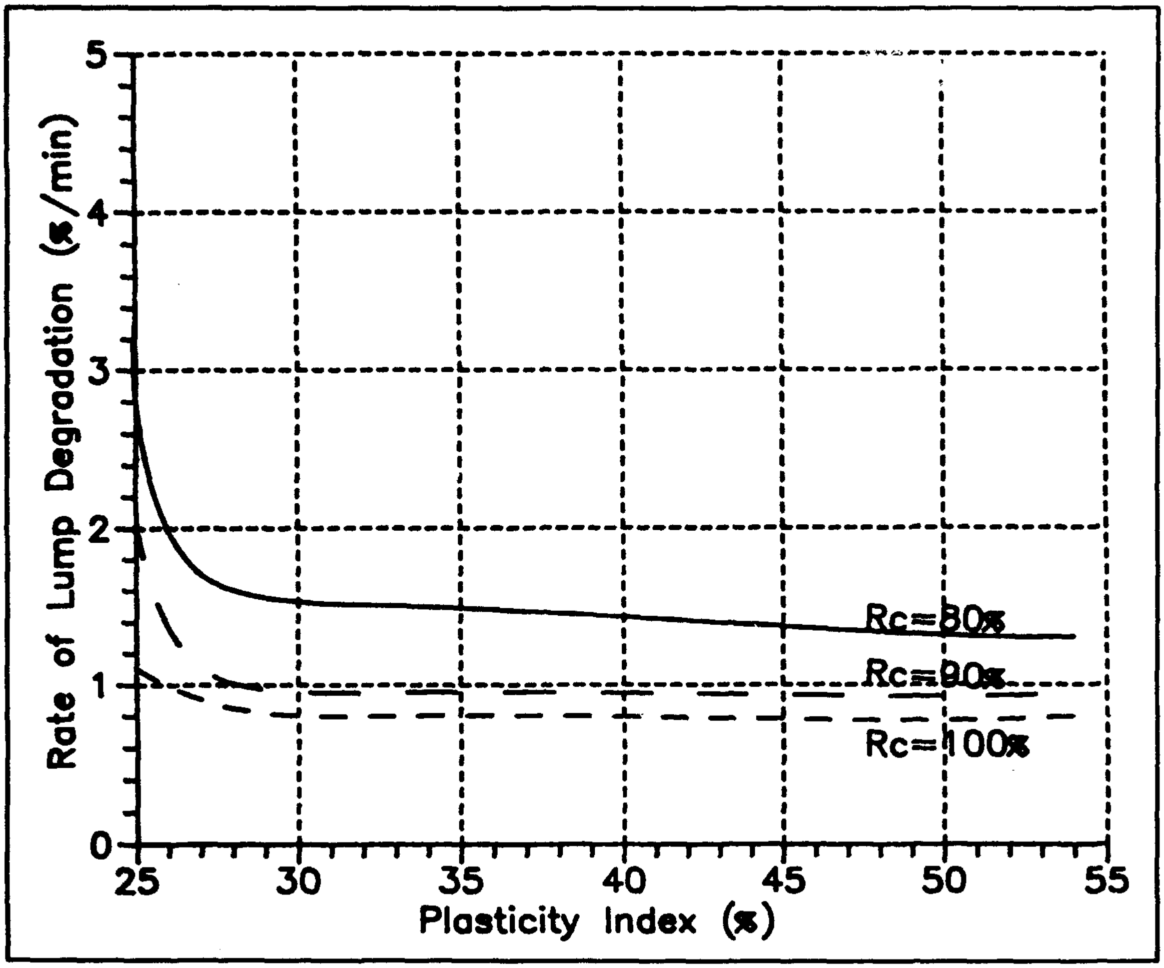


Figure 52. Rate of lump degradation versus PI for smooth drum test at $V = 2.4$ ft/sec

These figures show that decreasing PI and increasing velocity result in increased rate of degradation. Observing these figures as a group shows that at low compaction, plasticity is important in determining the rate of degradation. At higher compaction levels, however, rate of degradation is basically independent of plasticity; i.e., all clays tested basically degraded at the same rate.

Figures 50 through 79 have been condensed into two figures; i.e., Figures 80 and 81. Here, all the figures for a given test are presented on one page with the same vertical scale. Examining these figures, one realizes the effects of plasticity, compaction, and velocity on rate of degradation for the spin and rough drum test.

Smooth versus rough drum test

The difference in rate of degradation between the smooth and rough drum test at a velocity of 2.4 ft/sec is shown in Figure 82. As might be expected, rough conditions produce much greater degradation in lightly compacted materials at lower plasticities. The increased degradation effect of the rough

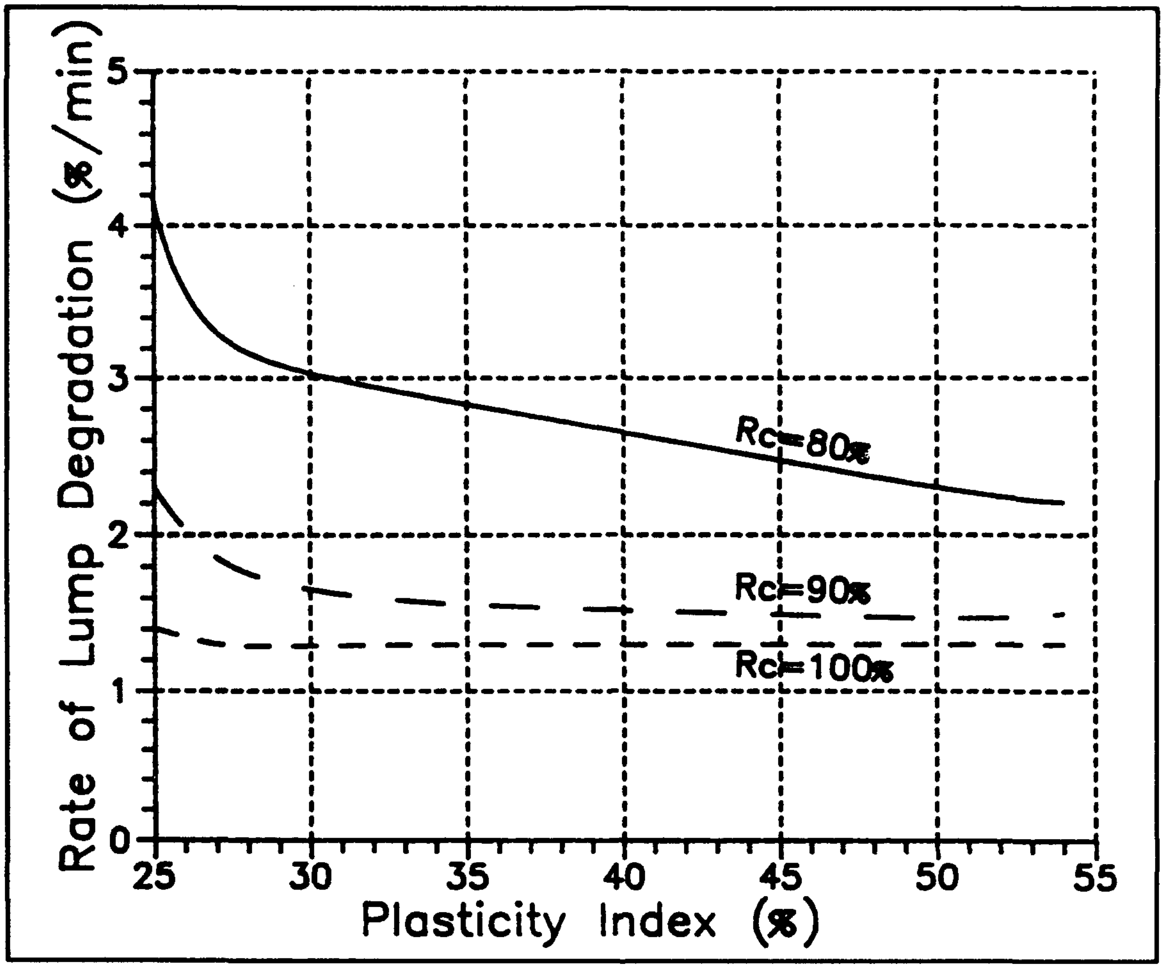


Figure 53. Rate of lump degradation versus PI for rough drum test at $V = 2.4$ ft/sec

drum on lightly compacted clay, however, is substantially reduced at higher plasticities. It can be seen that at a PI of about 50 percent, the difference in rate of degradation between the rough and smooth drum is only slight. At $Rc = 90$ percent and 100 percent, the difference in rate of degradation between the rough and smooth drum is negligible regardless of plasticity.

Summary of Trends Revealed

A summary of apparent trends is as follows:

a. For lightly compacted lean clay, rate of degradation increases rapidly as velocity increases. For lightly compacted fat clay, rate of degradation increase is slower (see Figure 77).

b. For lightly compacted material, a drastic decrease in rate of degradation occurs with just a slight increase in plasticity (see Figures 74 and 77).

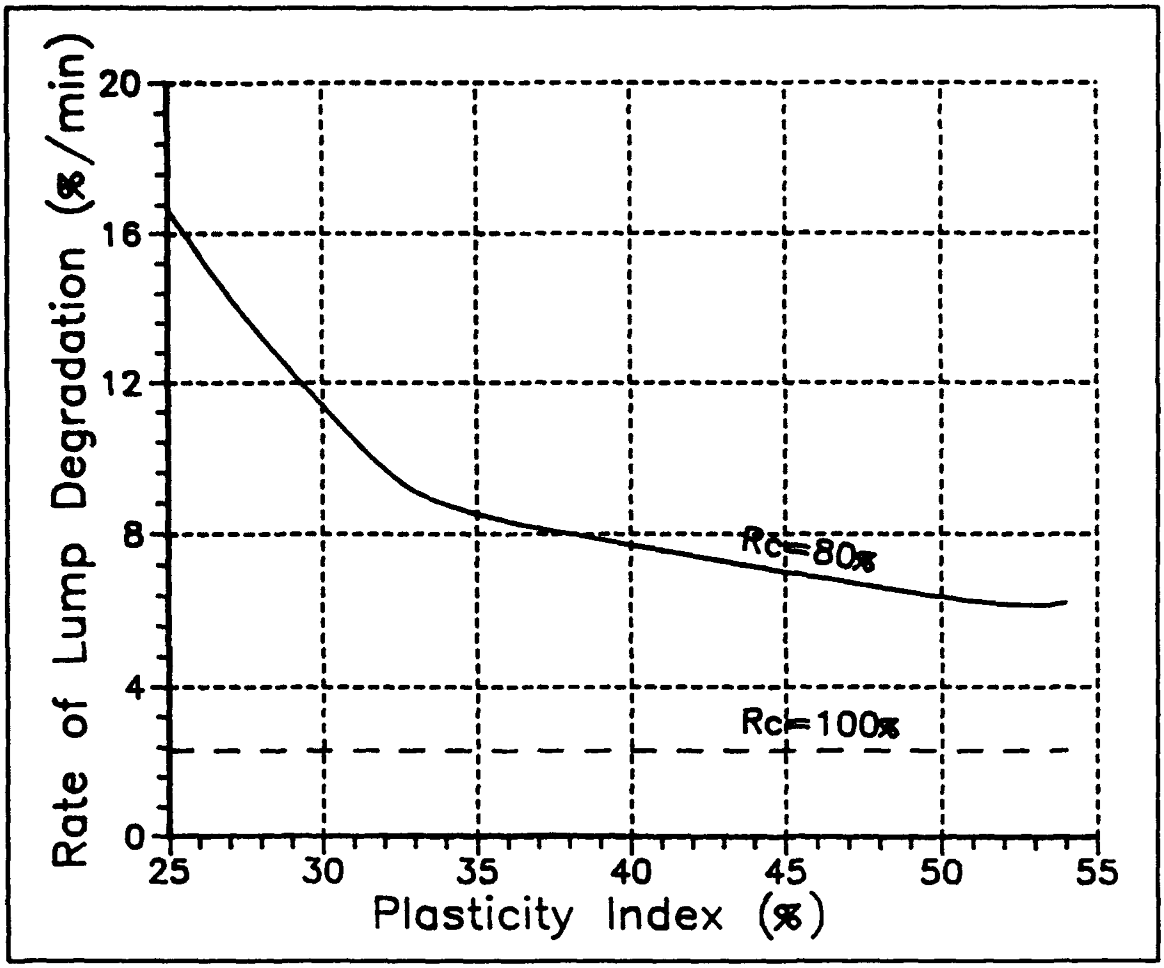


Figure 54. Rate of lump degradation versus PI for rough drum test at $V = 5$ ft/sec

c. For highly compacted material, rate of degradation is small even at high velocity, nearly regardless of plasticity (see Figure 76).

d. For highly compacted material, rate of degradation is relatively insensitive to velocity.

e. For lightly compacted material, the spin and drum tests provide different rates of degradation for the same apparent conditions. In the spin test, rate of degradation decreases rapidly as plasticity increases. In the drum test, however, the rate of decrease in degradation with increased plasticity is slower (compare Figures 74 and 77).

Comparison between the spin and drum tests

It is interesting to compare the spin tests with the rough drum tests. At low compaction levels and the same velocity, the spin test produces more rapid degradation. This result is probably due to densification of the loose and

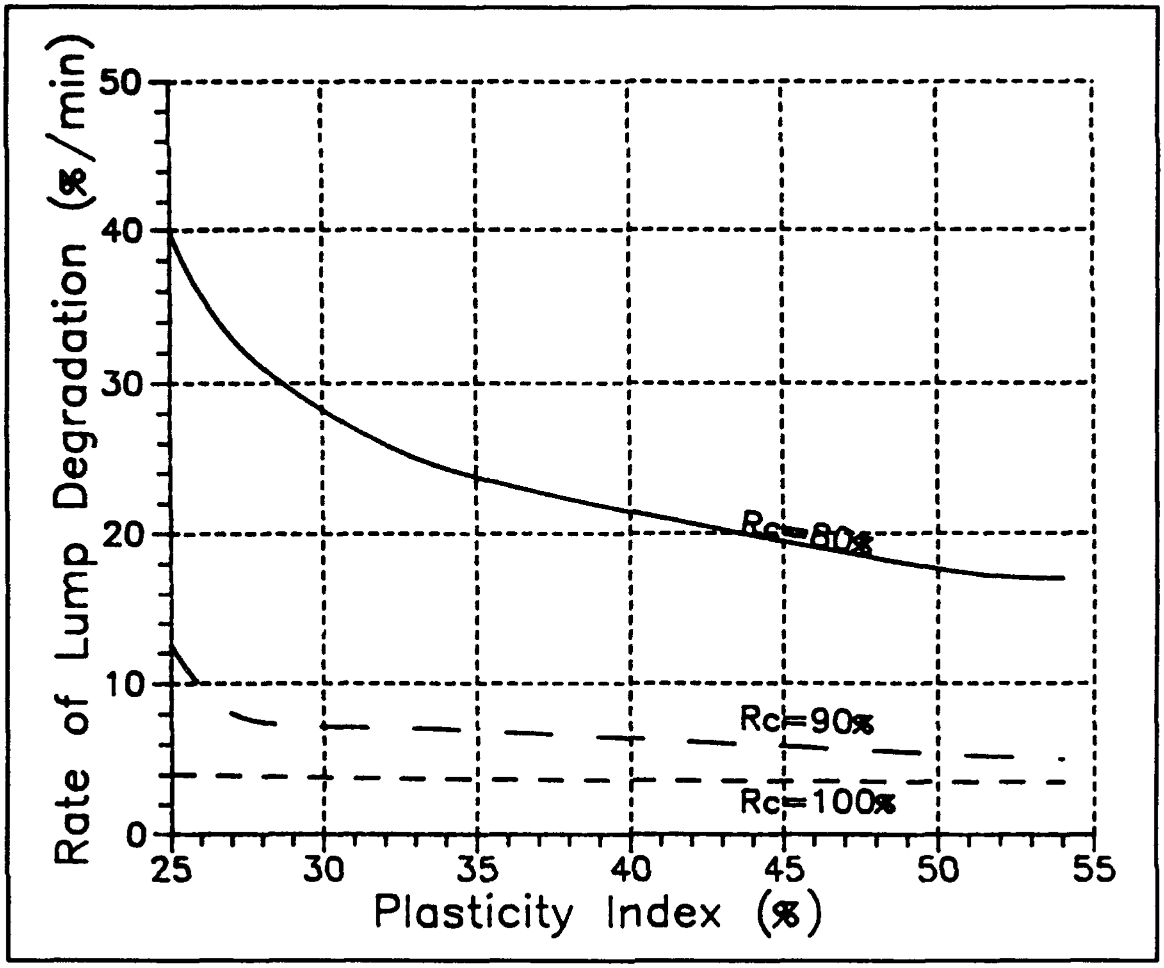


Figure 55. Rate of lump degradation versus PI for rough drum test at V = 7.5 ft/sec

plastic material as it pounds against the pipe (or drum) walls. This causes the loose material to experience a strength gain as it is transported, thus gaining an increased resistance to degradation. Conversely, highly compacted material is near its maximum density. This material is difficult to further compact and therefore very little change in strength can occur during the transport.

Relevance to clay balling

The tests may provide some clues as to when the phenomenon known as clay balling might occur. Clay balls develop when lumps in transport either resist degradation (or slurrification) or, in a more extreme case, progressively stick together, forming larger and larger balls that may eventually clog the pipe. Consistent observations of all the figures in this chapter reveal a noticeable change occurring in clay behavior between PI = 25 percent and PI = 35 percent. For PI at 25 percent the material is very friable unless heavily compacted. For PI between 25 percent and 35 percent, material becomes

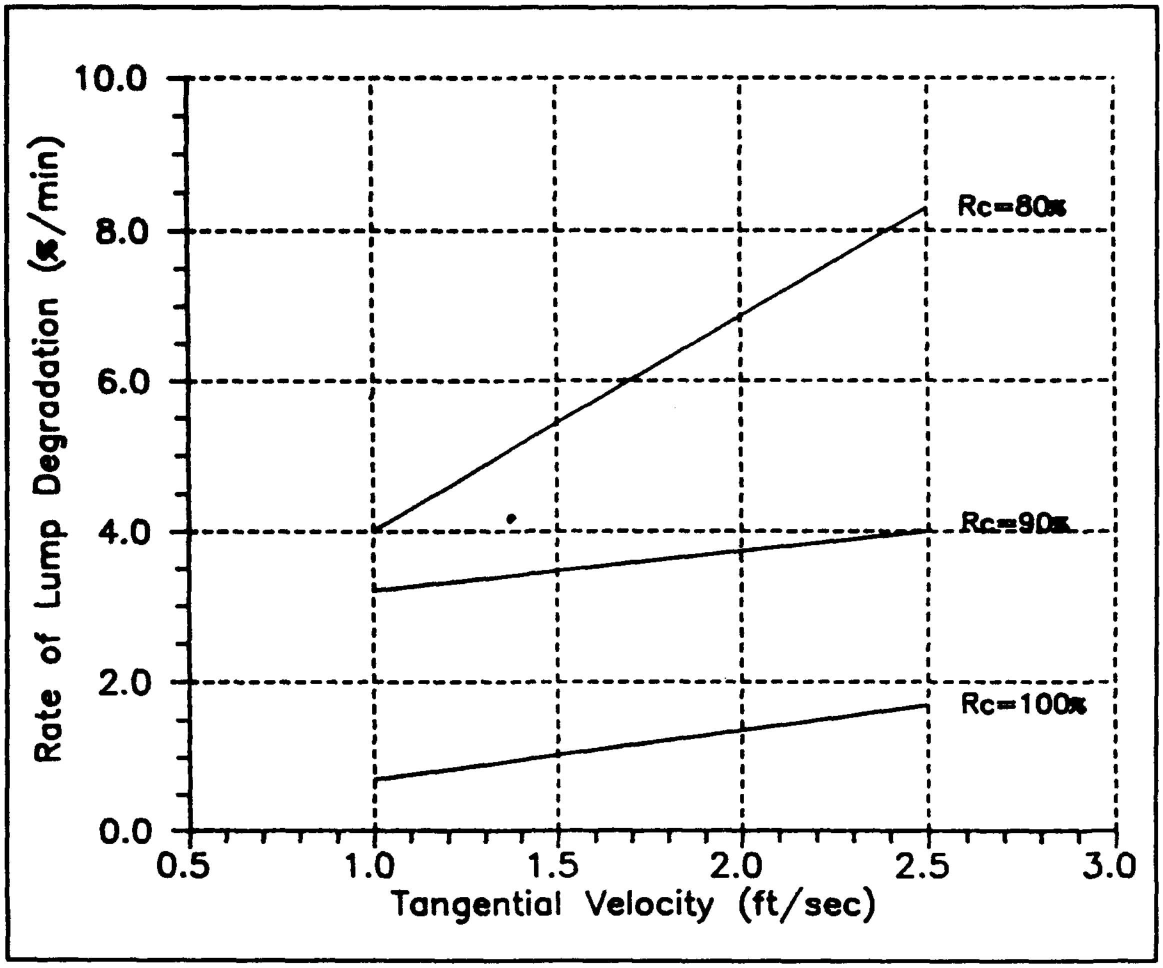


Figure 56. Rate of lump degradation versus *V* for spin test at PI = 25 percent

progressively less friable at lower compaction and relatively unfriable at higher compaction. For PIs above 35 percent, however, the material resists degradation even at low compaction levels. It is therefore generally felt that, for plasticities under 25 percent, no clay balling will occur. For plasticity between 25 percent and 35 percent, clay balling is not likely unless the material is very dense. For clays with plasticity above PI = 35 percent, however, clay balling is likely even for lightly compacted material. That is, the "stickiness" due to high plasticity is significant enough to allow cementation of lumps which turn into balls.

Design Charts and Procedure for Use in Calculating Degradation

Figures 77 through 79 can be utilized as design charts to make predictions of the rate of degradation. It is felt that these charts, which are based on the rough drum test, best correspond to the actual conditions in a dredge line. The steps needed to make predictions are as follows:

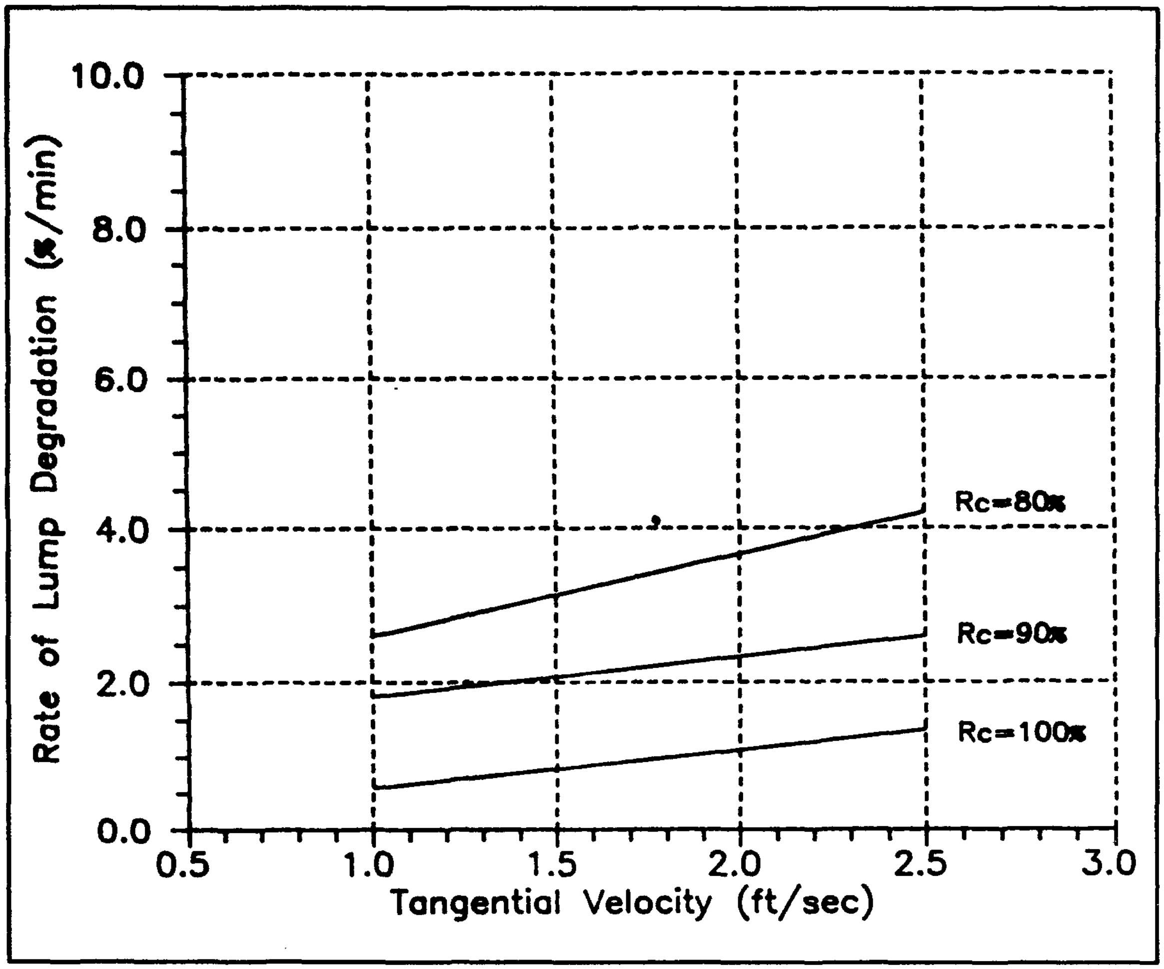


Figure 57. Rate of lump degradation versus *V* for spin test at PI = 26 percent

a. Measure plasticity index (ASTM D-4318) and in situ dry unit weight. In situ dry unit weight can be found using a variation of ASTM D-2922, "Density of Soil and Soil-Aggregate In Place by Nuclear Methods," modified for underwater testing. A very efficient method of determining continuous underwater soil density has been developed in Holland by Delft Hydraulics Lab (Dunlap 1989).

b. Determine the materials maximum dry unit weight by the Standard Proctor Compaction Test (ASTM D-698).

c. Divide the in-place dry unit weight by the maximum dry unit weight and multiply by 100. This is the relative compaction *Rc* of the clay.

d. Select a pipe size, effluent (fluid and solid) pumping rate, and estimate material production.

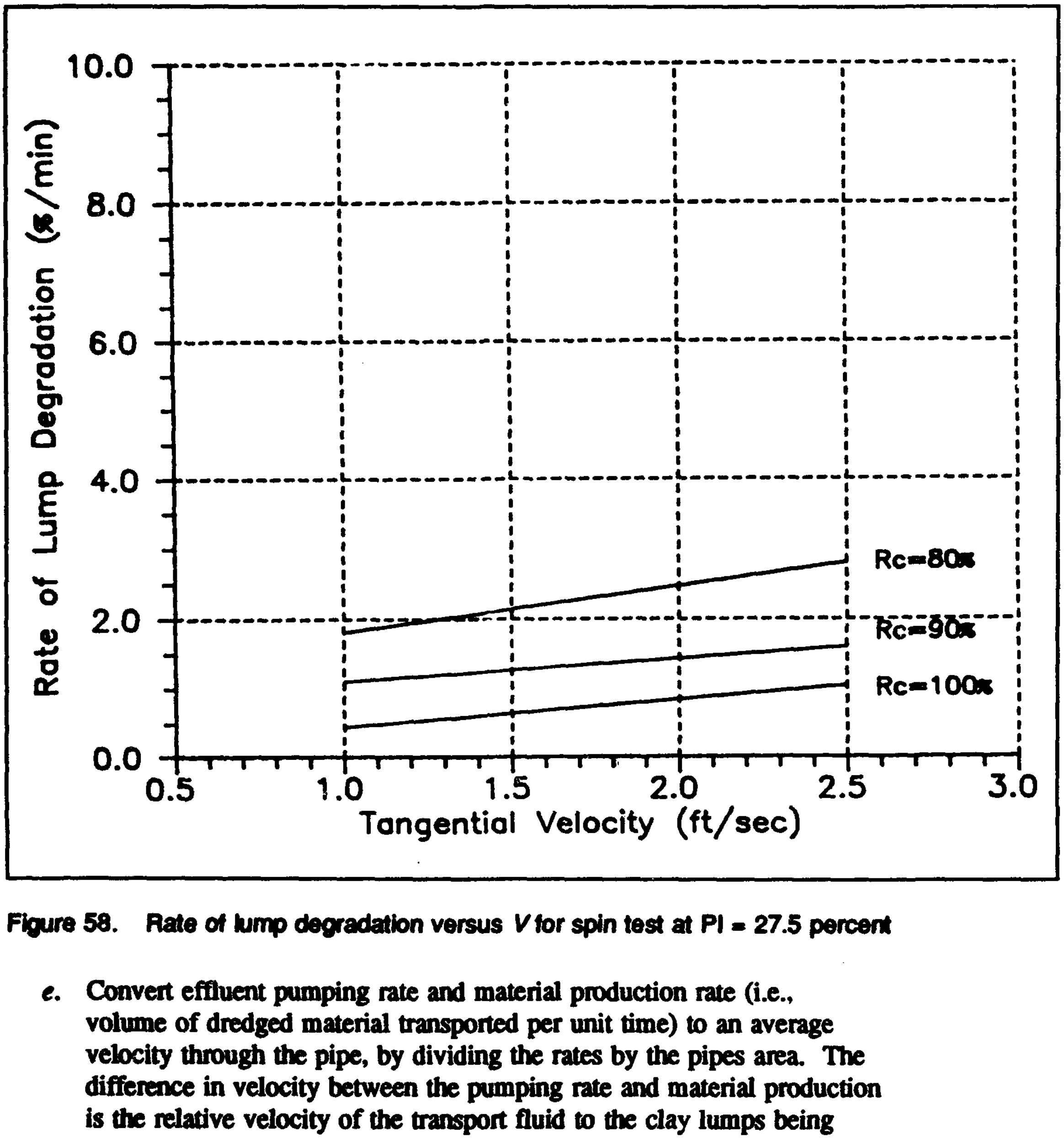


Figure 58. Rate of lump degradation versus *V* for spin test at PI = 27.5 percent

e. Convert effluent pumping rate and material production rate (i.e., volume of dredged material transported per unit time) to an average velocity through the pipe, by dividing the rates by the pipes area. The difference in velocity between the pumping rate and material production is the relative velocity of the transport fluid to the clay lumps being dragged. Note: It is likely that the velocity of the lumps is small compared to the velocity of the transport fluid. This is normally the case since clay lumps are too heavy to be carried in suspension as sands are, but, rather, are dragged as a moving bed along the bottom of the pipe.

f. Using the appropriate chart from Figures 77 through 79 for the material's relative compaction (some interpolation between charts may be necessary), enter the relative velocity of the dredged clay lumps to the transport fluid.

g. Enter the material's plasticity (PI) and read the expected rate of degradation.

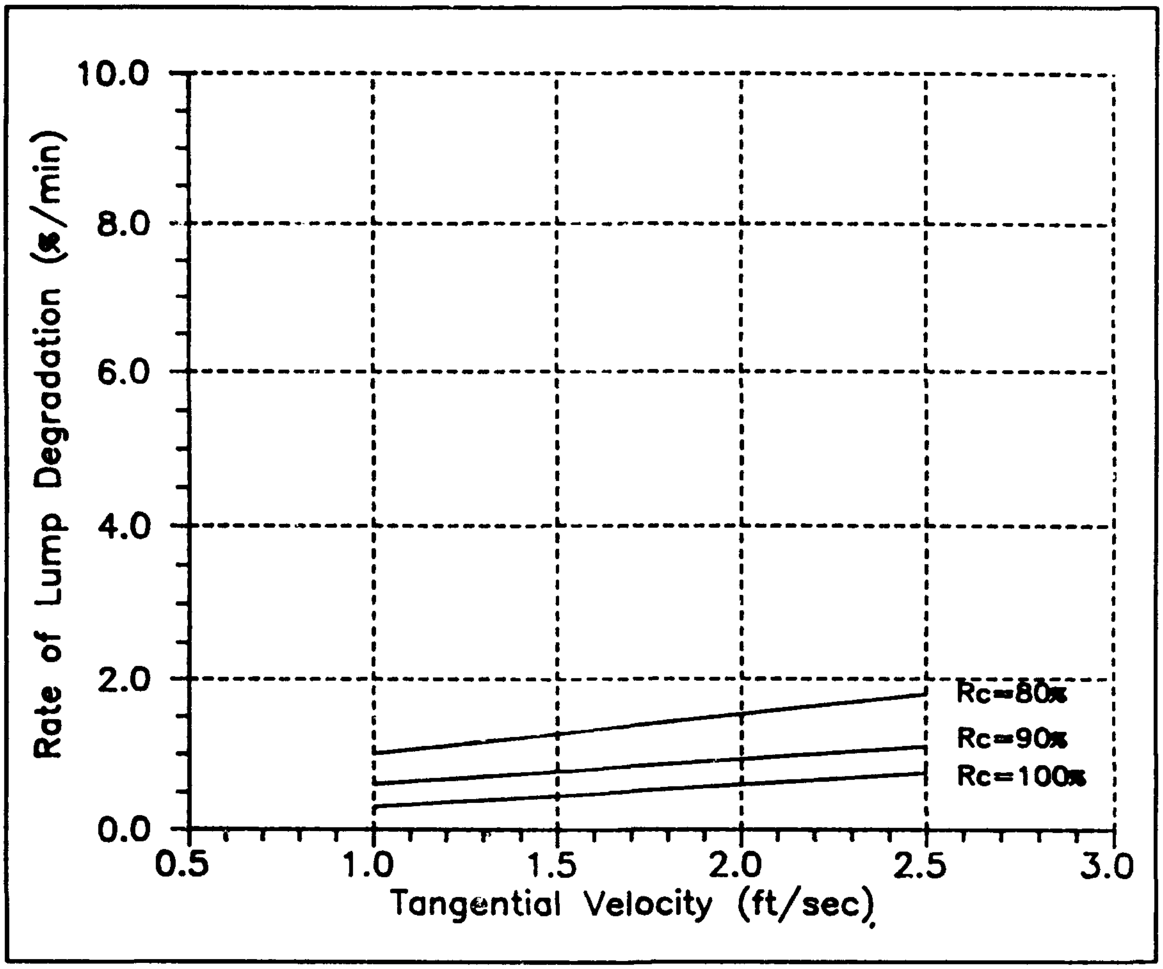


Figure 59. Rate of lump degradation versus *V* for spin test at PI = 30 percent

h. Knowing the pipeline distance to the disposal area and velocity of the clay lumps, compute the time lumps will undergo hydraulic transport.

i. Multiply the time lumps are in hydraulic transport by the rate of degradation to find ultimate clay lump degradation.

Example 1

A soil investigation reveals that the PI of a clay to be dredged is 30 percent. Unit weight of the in-place material is found to be 68 pcf. The clay maximum Proctor density is 85.2 pcf. A hydraulic suction cutterhead dredge with a 16-in. discharge will be used for the project. The cutterhead is expected to cut lumps with an average size of 1/30 cu ft. The material will be pumped through a 16-in. pipe a distance of 1,000 ft to the discharge area. The pumping rate of the effluent is expected to be 4,000 gal/min. Material production rate is expected to be 200 cu yd/hr. The ultimate degradation of an average lump is found as follows:

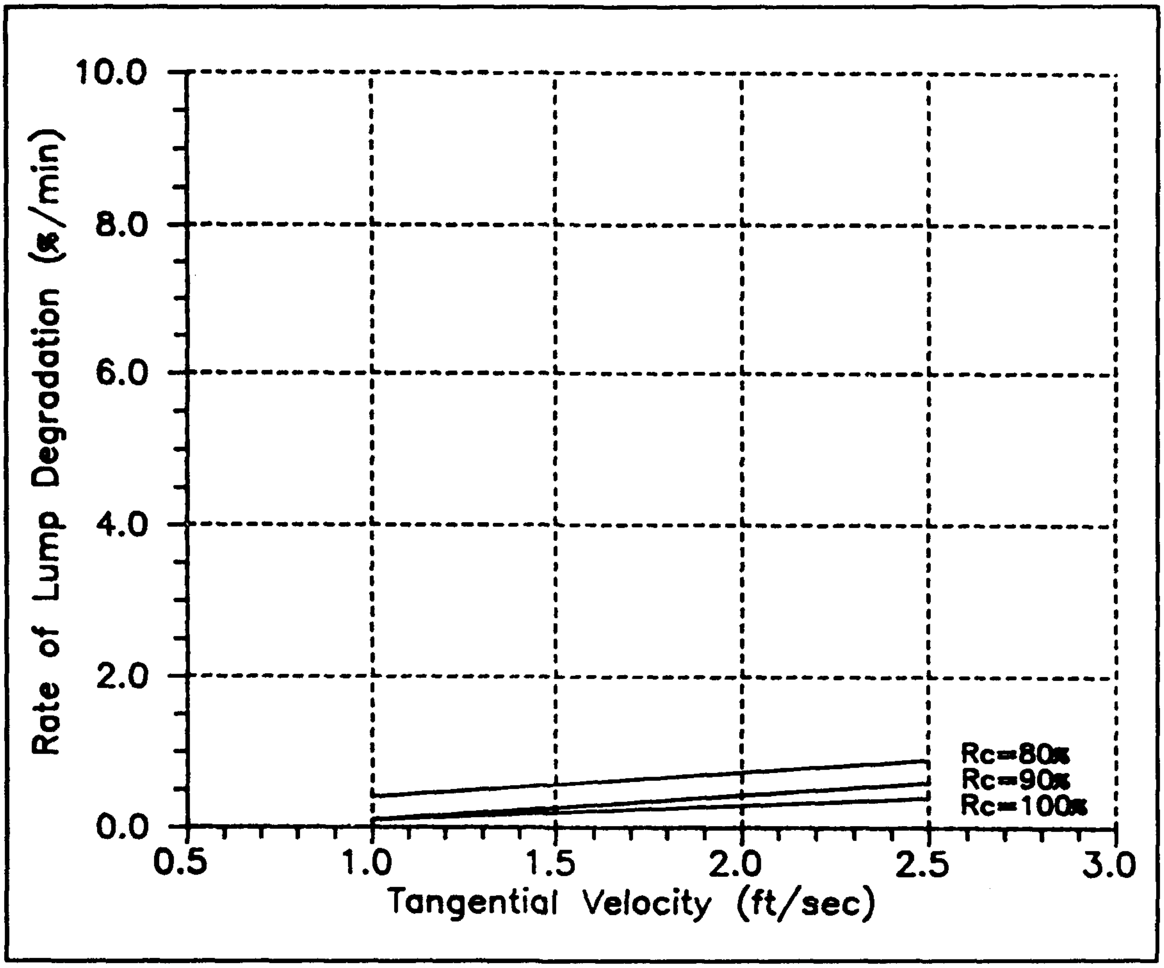


Figure 60. Rate of lump degradation versus *V* for spin test at PI = 35 percent

a. Find the relative compaction of the clay: (68/85.2)*100 = 80 percent.

b. Convert effluent flow rate to cu ft/sec.:
(4000*0.1337/60) = 8.9 cu ft/sec.

c. Convert pipe diameter to feet: 16 in. = 1.33 ft.

d. Find effluent average velocity: 8.9/[(1.33^2*3.14)/4] = 6.4 ft/sec.

e. Find material transport average velocity:
200*27)/[1.33^2*3.14)/4]/3600 = 1.1ft/sec.

f. Find relative velocity of material to transport fluid: 6.4 - 1.1 = 5.3 ft/sec.

g. Using a pipeline length of 1,000 ft, the material transport time is:
1000/1.1 = 910 sec = 15.2 min.

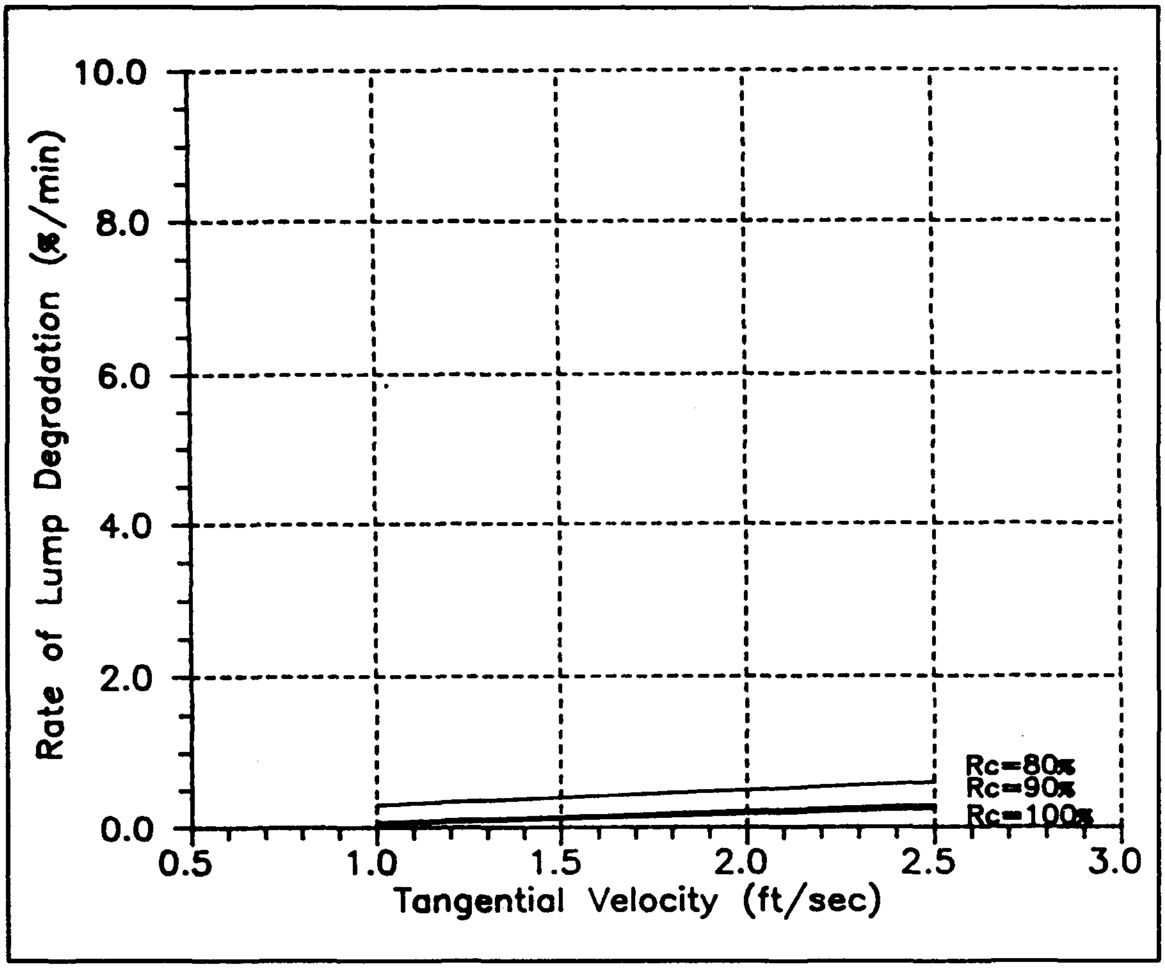


Figure 61. Rate of lump degradation versus *V* for spin test at PI = 40 percent

h. Finally, with PI = 30 percent and *Rc* = 80 percent, and using Figure 77, the rate of degradation is 13 percent /min.

i. The ultimate degradation (taking the rate to be linear--see test results) is: 15.2 * 13 = 198 percent > 100 percent.

Clearly, the cut clay lumps will degrade into suspension within 7.7 min (i.e., before traveling 500 ft through the pipeline). That is, the material will slurrify rapidly.

The following conclusions can be drawn from the example problem regarding the clay's expected behavior when dredged:

a. The material can be easily pumped.

b. The material is not likely to clog the pipeline or the pump.

c. The material will require containment at the discharge area.

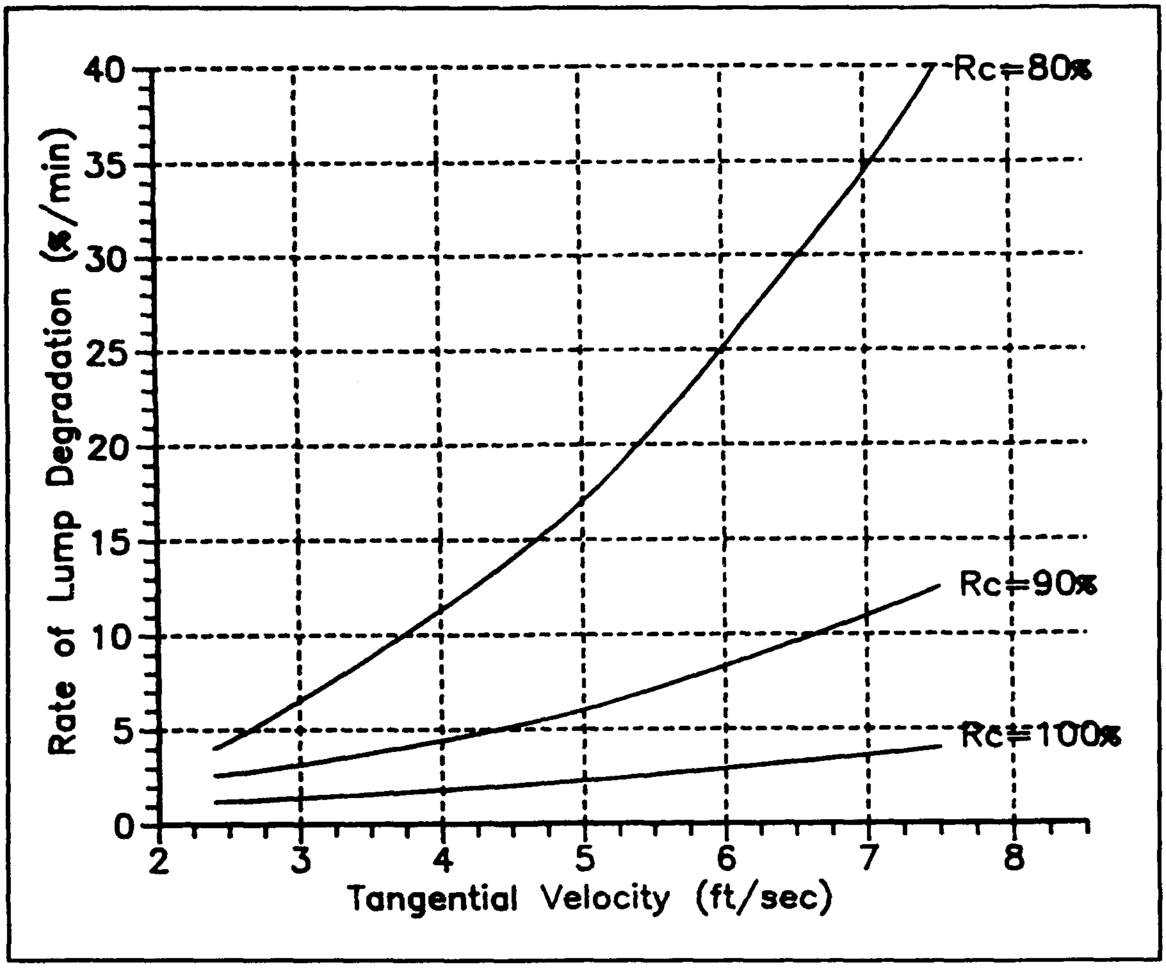


Figure 62. Rate of lump degradation versus *V* for rough drum test at PI = 25 percent

d. It will require time for solids to settle out of suspension and to consolidate.

e. Initially the material will not be good for dike construction.

Example 2

A soil investigation is performed on a second area to be dredged. The material is clay and the PI is found to be 50 percent. The clay *Rc* = 100 percent. The pumping distance to the disposal area in this case is 600 ft. All other conditions are the same as in Example 1.

a. The material transport time is: 600/1.1 = 545 sec = 9.1 min.

b. With PI = 50 percent, *Rc* = 100 percent, and using Figure 79, the rate of degradation is 2.2 percent /min.

c. The ultimate degradation is: 9.1*2.2 = 20 percent.

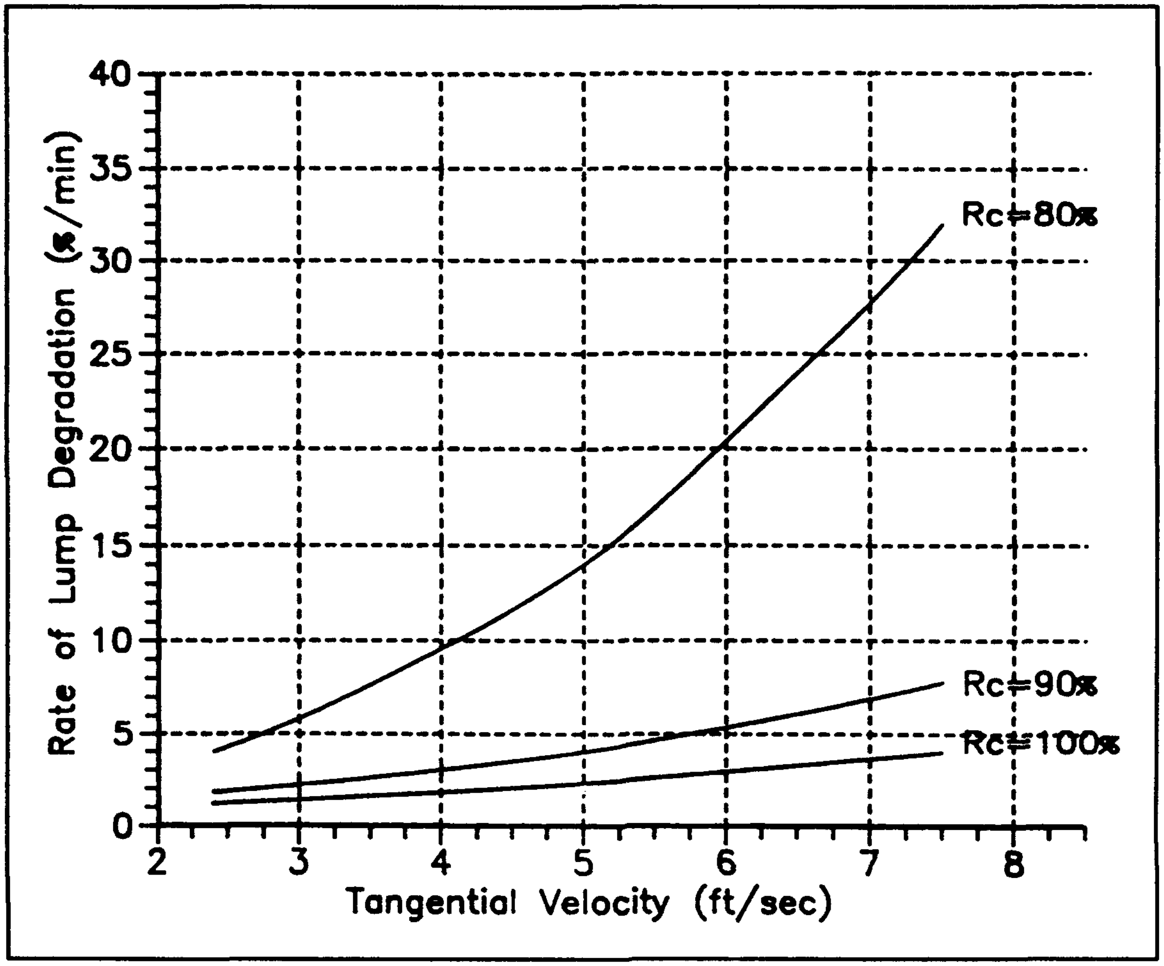


Figure 63. Rate of lump degradation versus *V* for rough drum test at PI = 27.5 percent

Subsequently, the clay lumps will undergo very little degradation. Actually, balling is very likely to occur. The following conclusion can be drawn for the second example regarding the clay's behavior when dredged:

a. The clay will be relatively difficult to pump.

b. The material may clog the pipe or pump if cut in large pieces.

c. The material will require little containment at the discharge area.

d. The material will settle out of suspension rapidly.

e. The material will be adequate for dike construction.

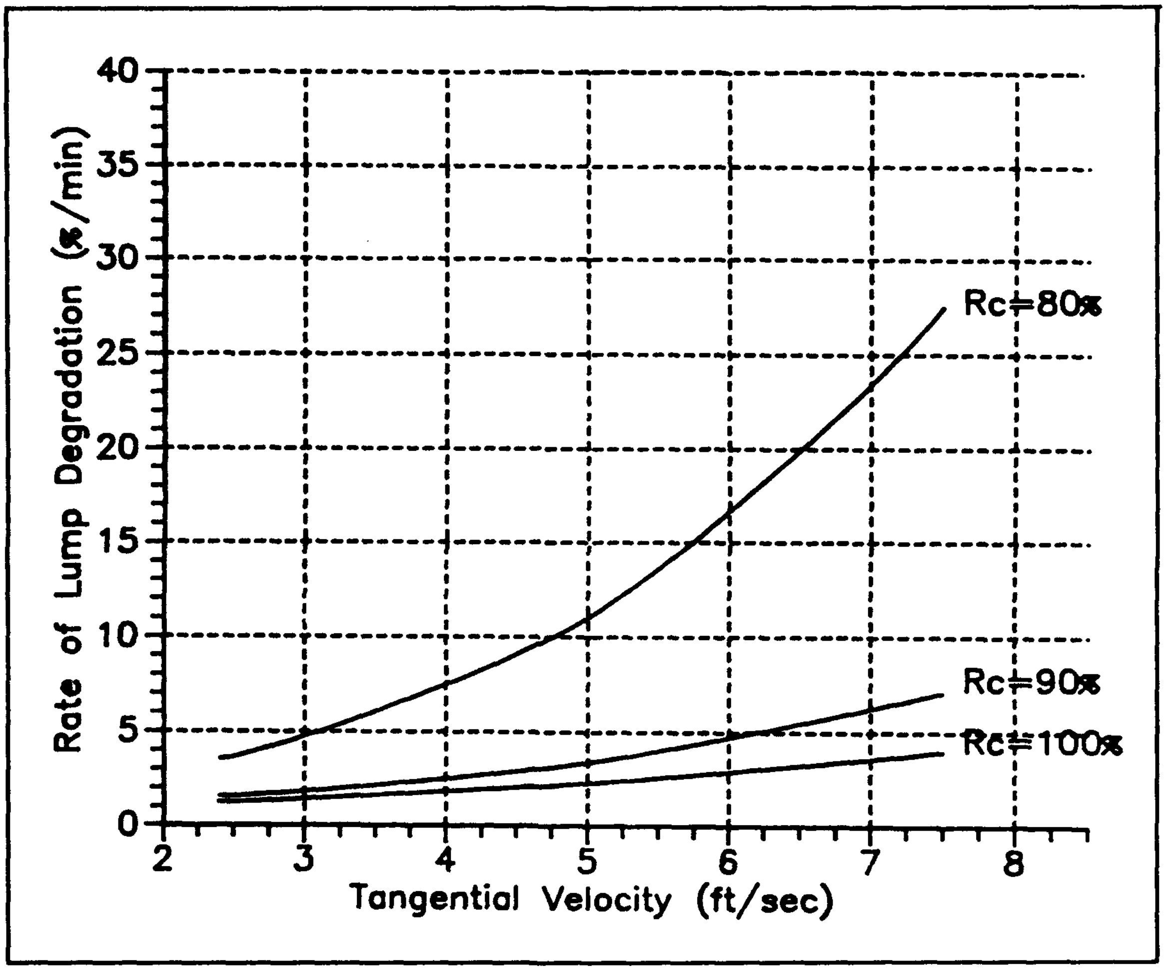


Figure 64. Rate of lump degradation versus *V* for rough drum test at PI = 30 percent

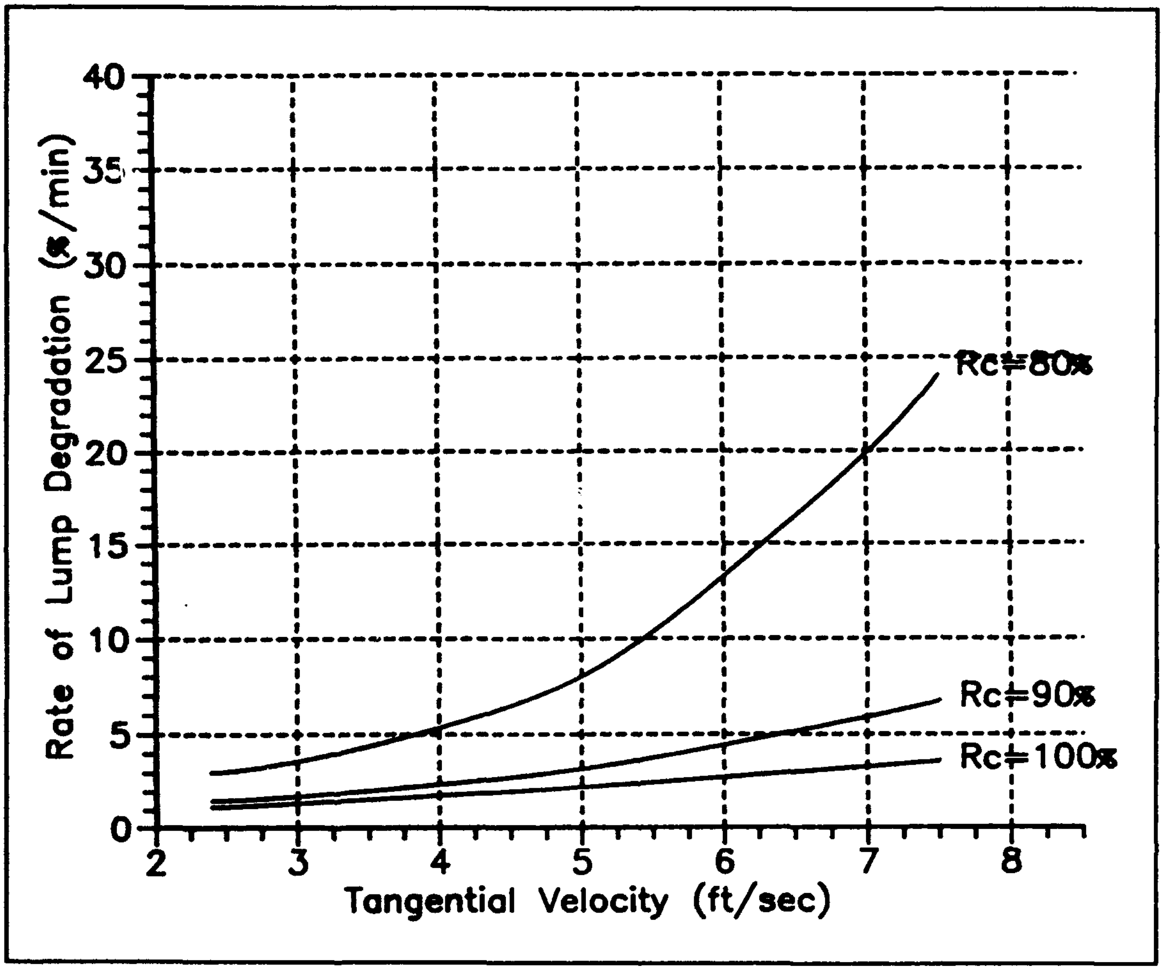


Figure 65. Rate of lump degradation versus *V* for rough drum test at PI = 35 percent

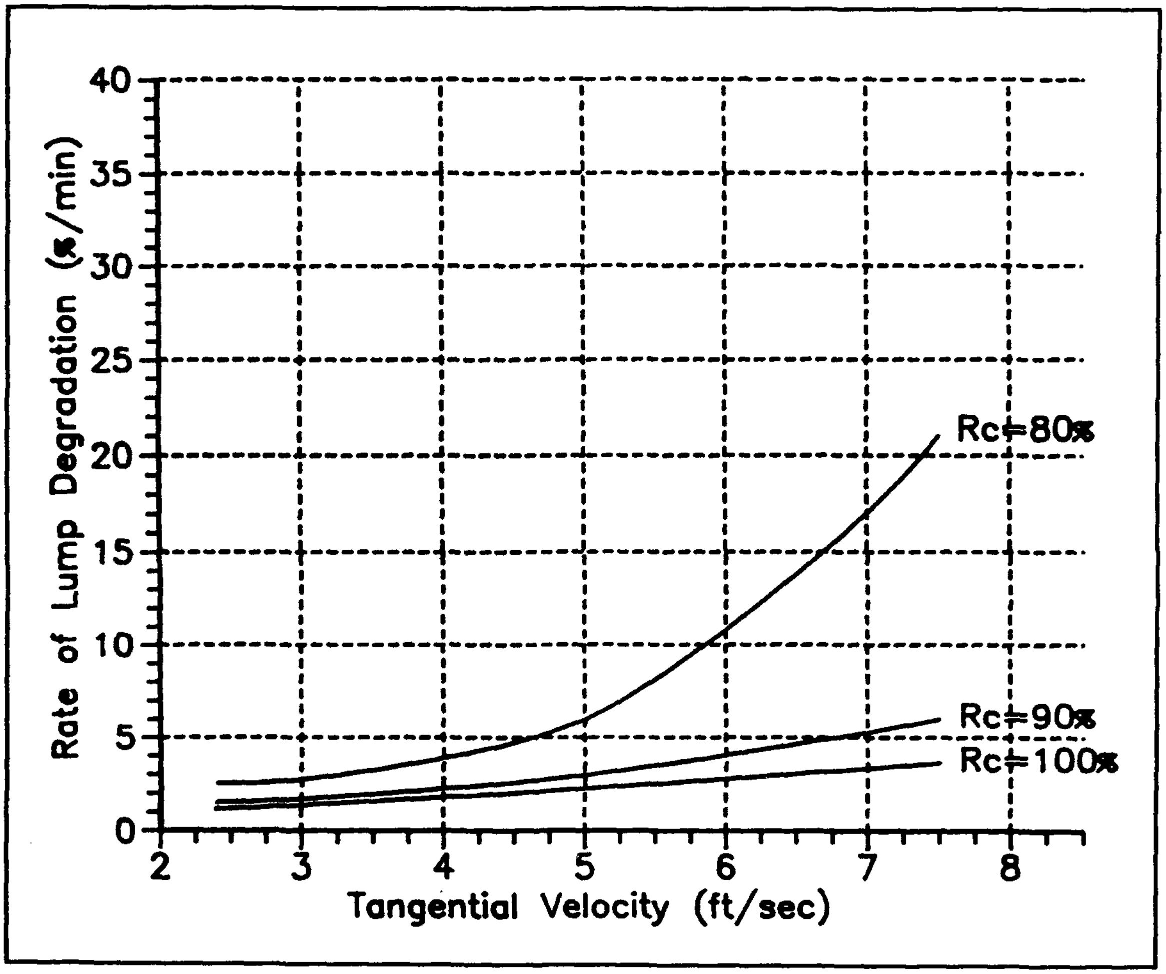


Figure 66. Rate of lump degradation versus *V* for rough drum test at PI = 45 percent

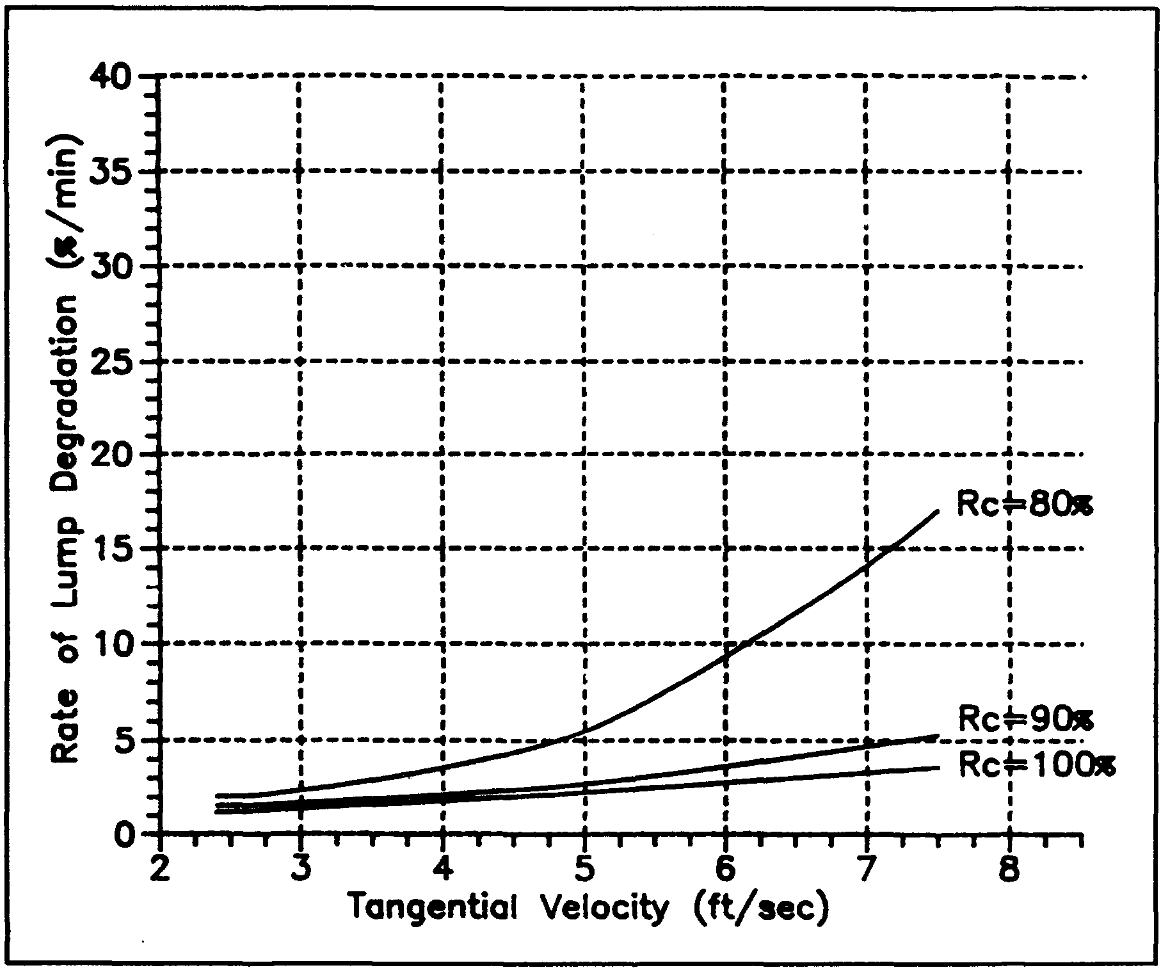


Figure 67. Rate of lump degradation versus *V* for rough drum test at PI = 54 percent

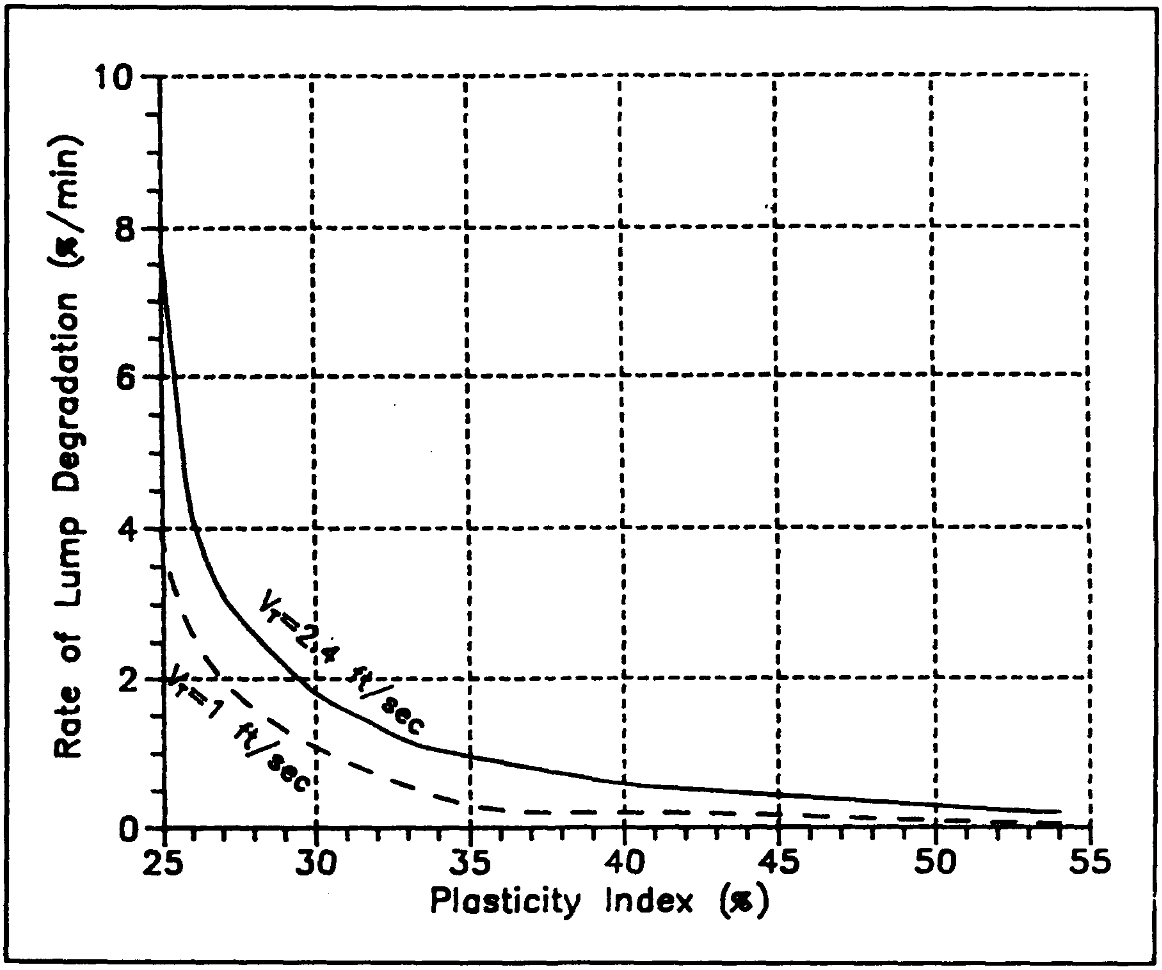


Figure 68. Rate of lump degradation versus PI for spin test at Rc = 80 percent

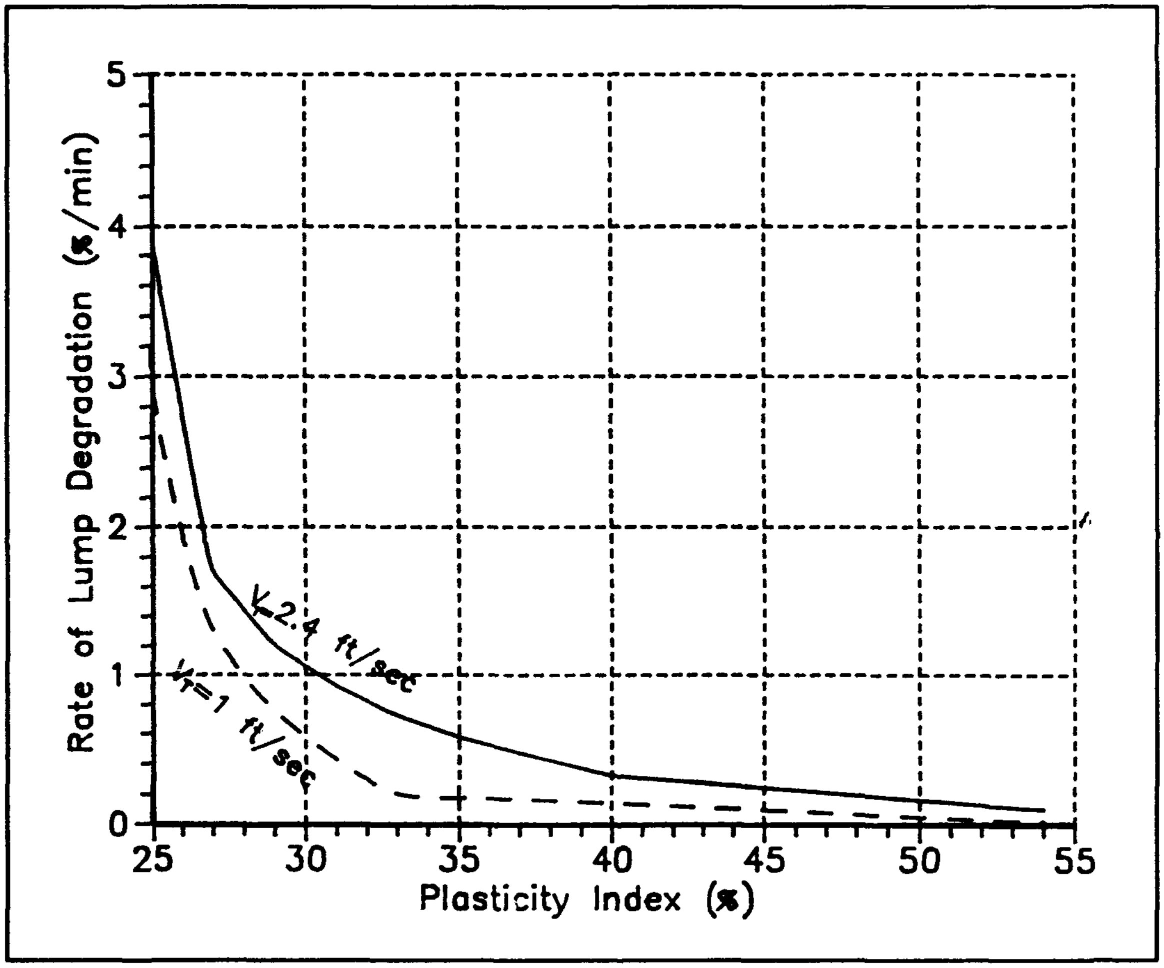


Figure 69. Rate of lump degradation versus PI for spin test at *Rc* = 90 percent

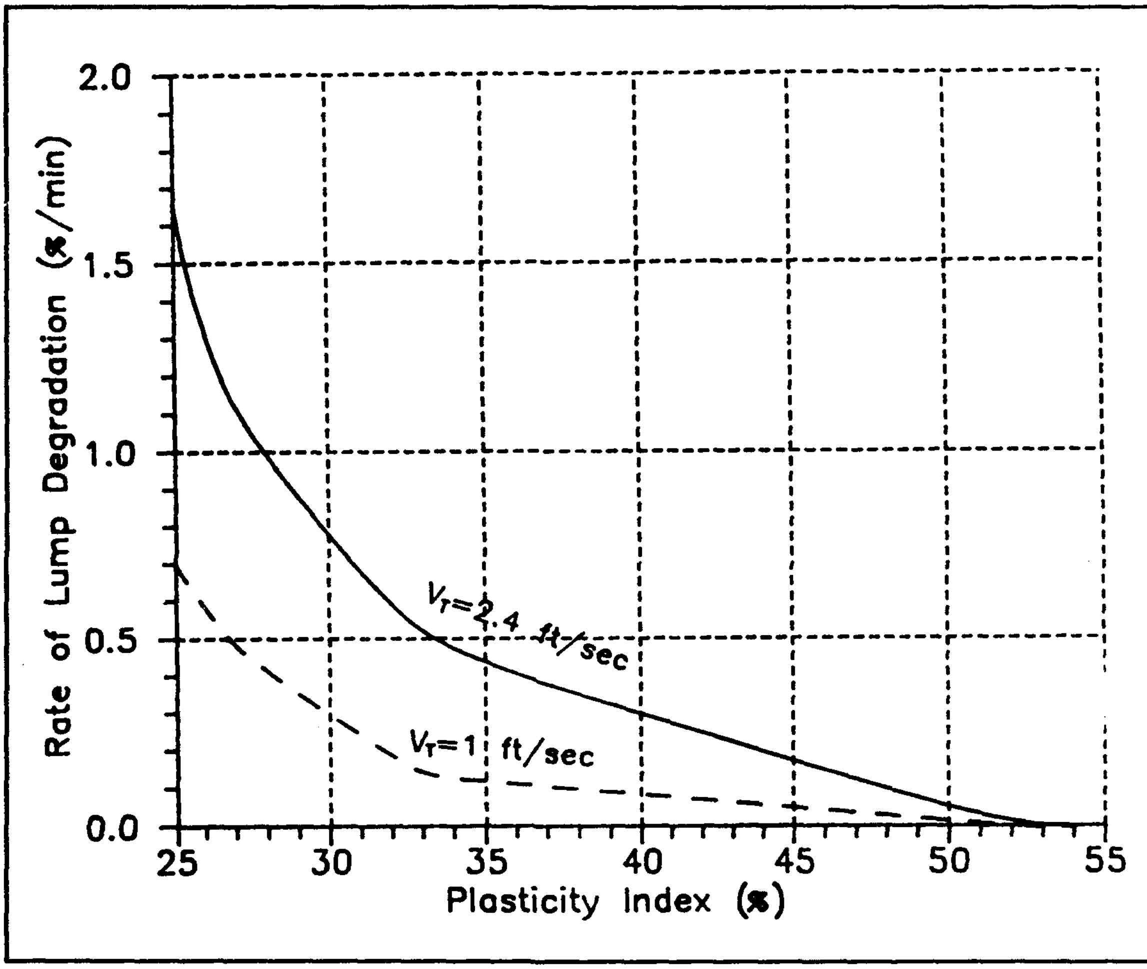


Figure 70. Rate of lump degradation versus PI for spin test at Rc = 100 percent

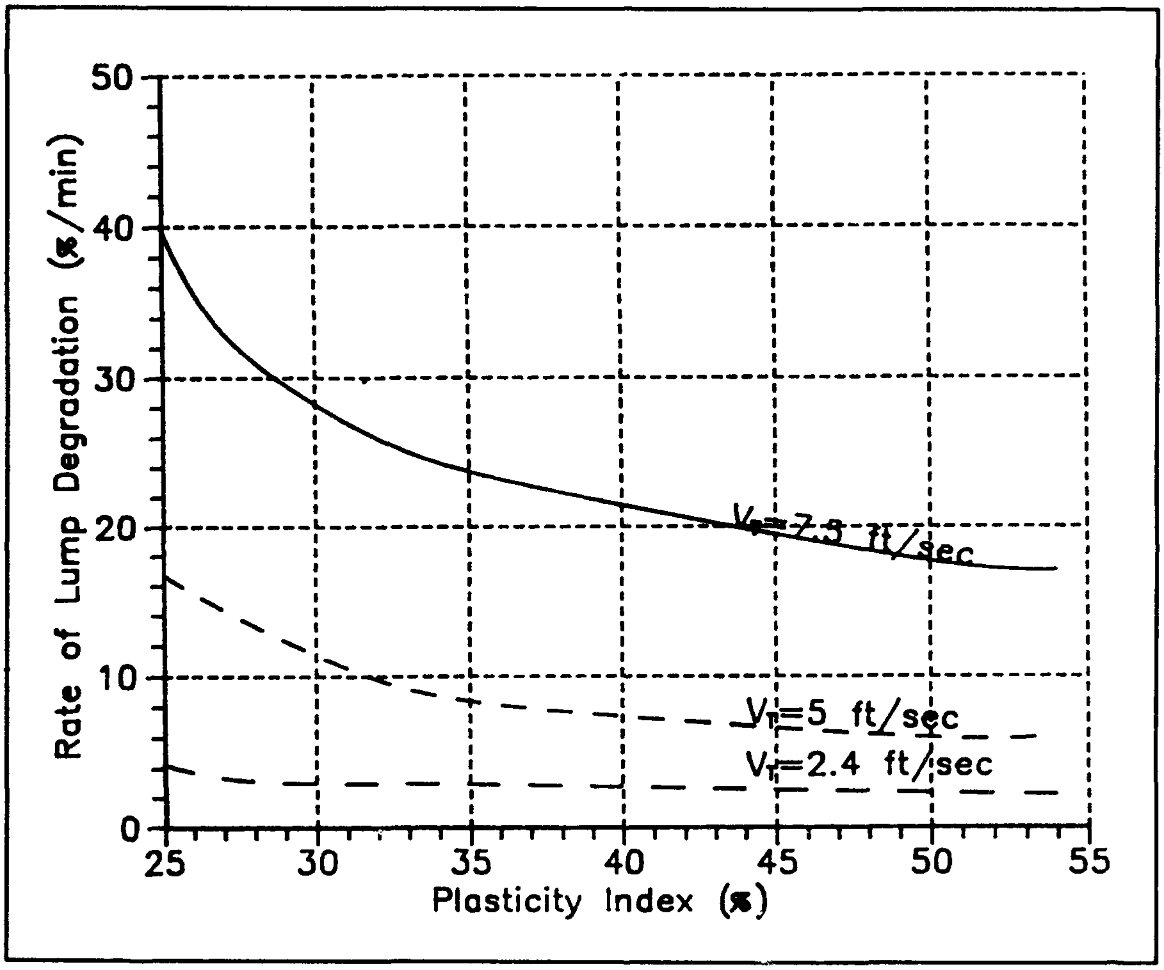


Figure 71. Rate of lump degradation versus PI for rough drum test at *Rc* = 80 percent

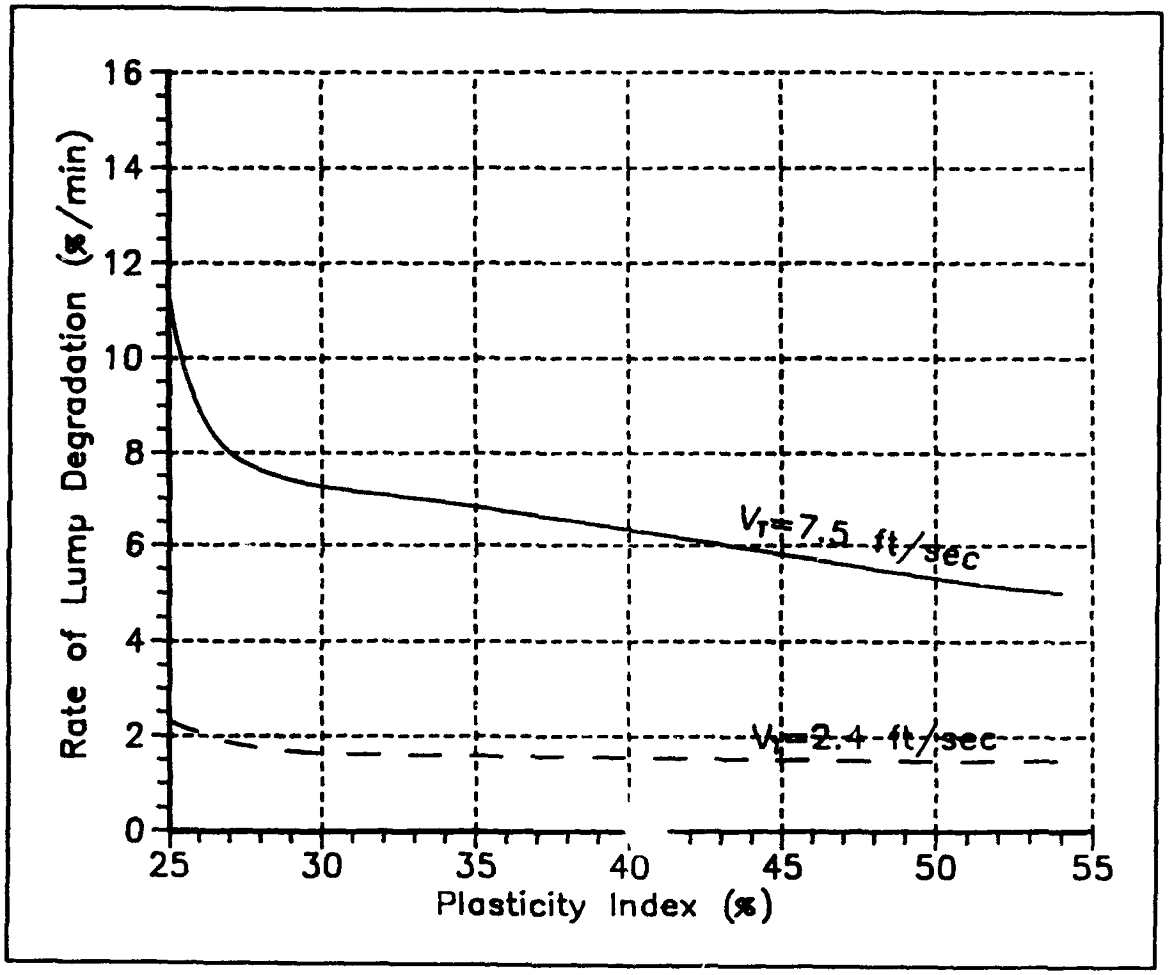


Figure 72. Rate of lump degradation versus PI for rough drum test at Rc = 90 percent

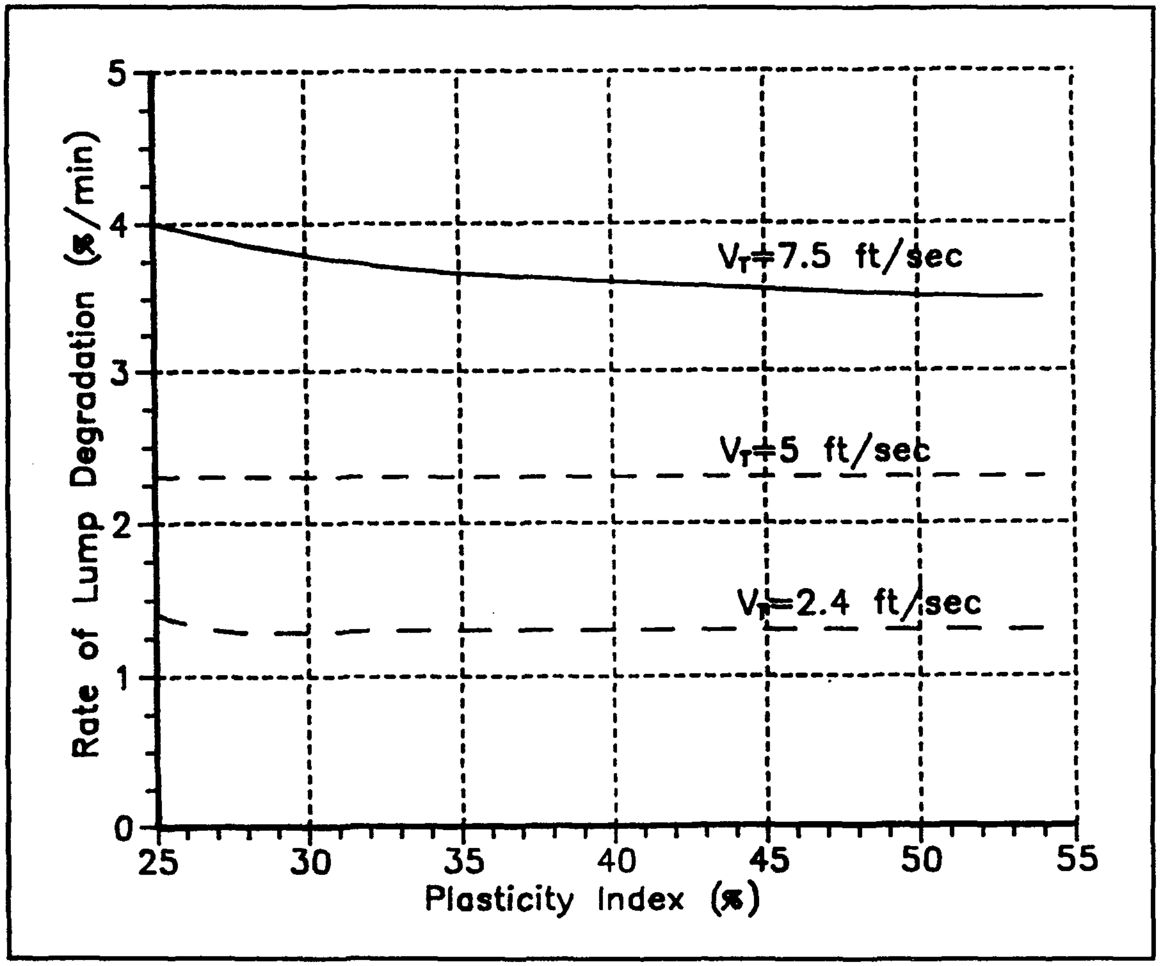


Figure 73. Rate of lump degradation versus PI for rough drum test at *Rc* = 100 percent

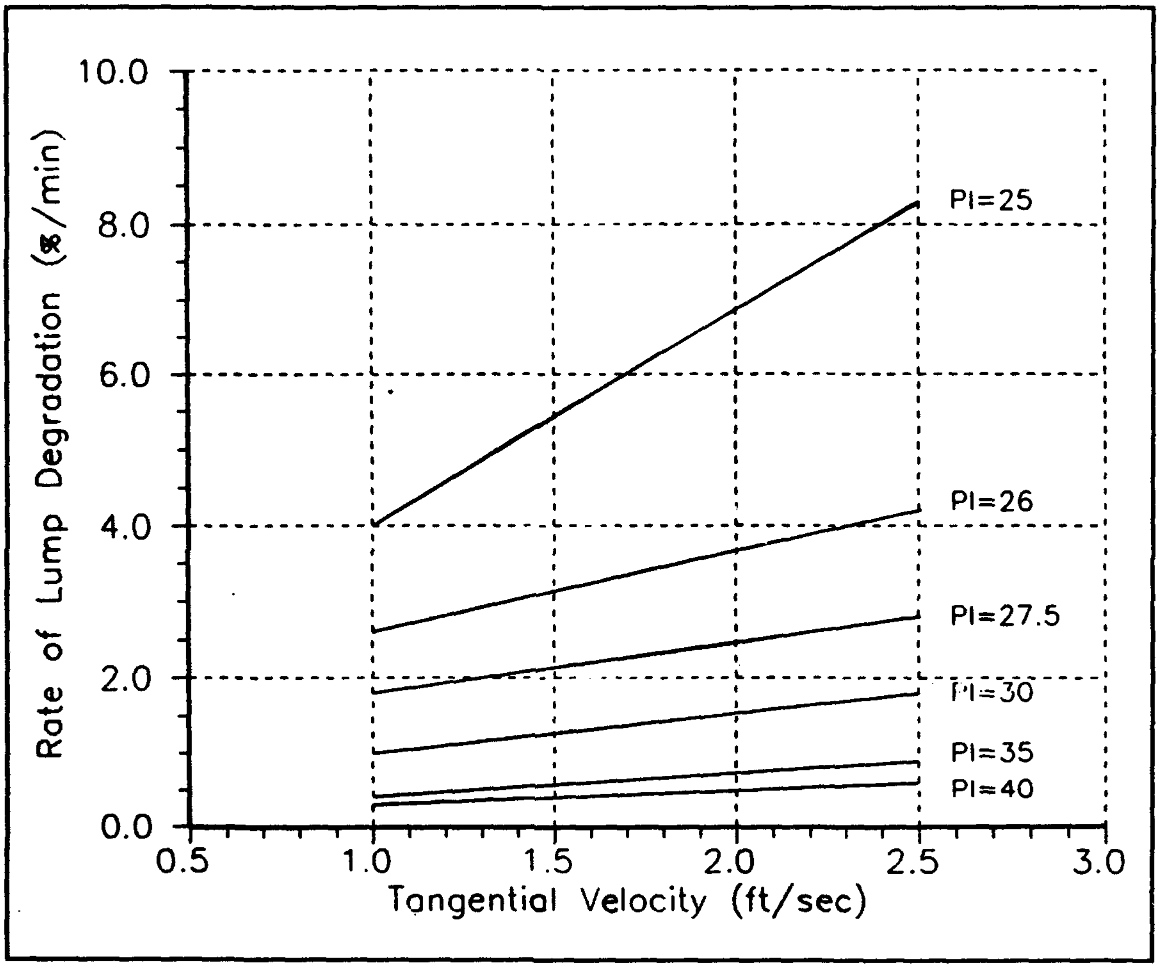


Figure 74. Rate of lump degradation versus V for spin test at *Rc* = 80 percent

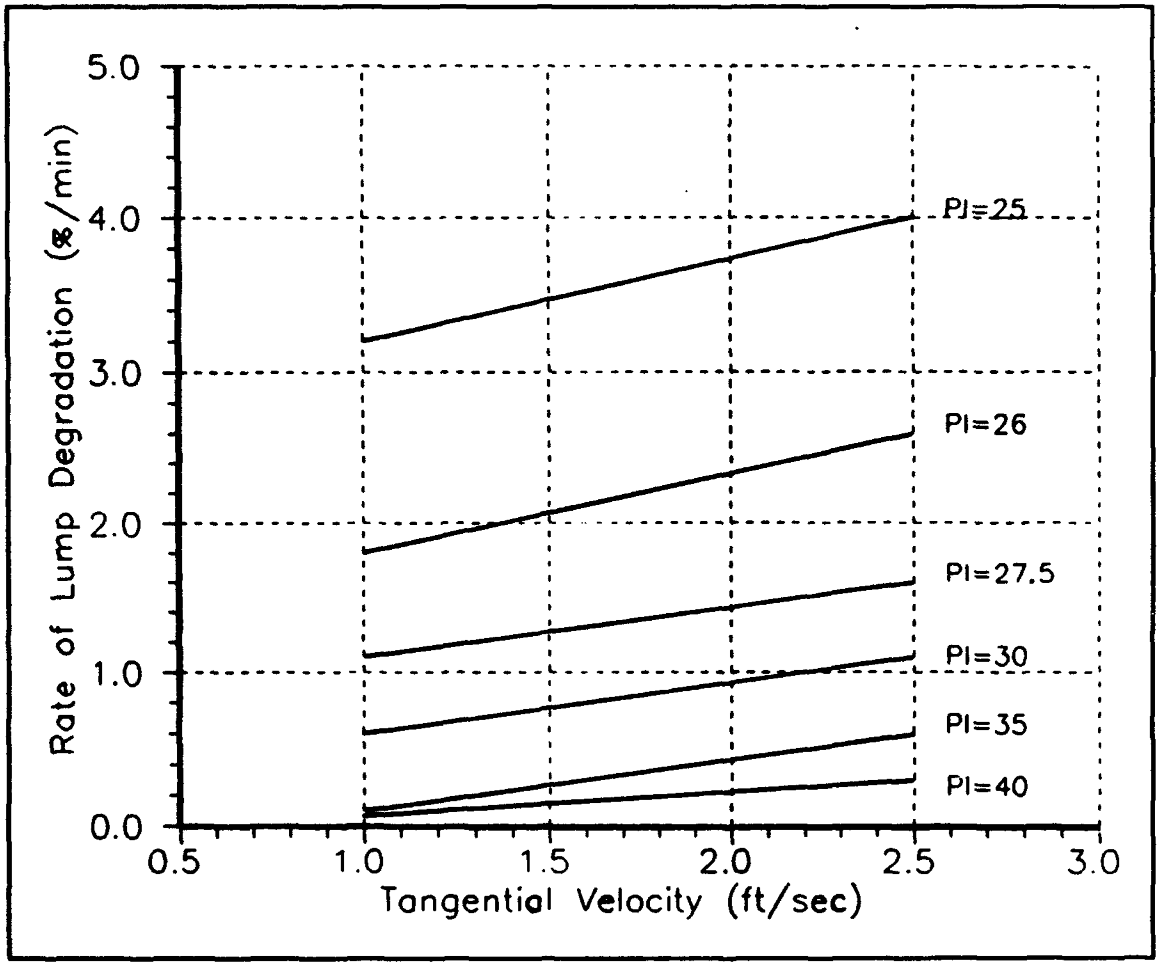


Figure 75. Rate of lump degradation versus V for spin test at Rc = 90 percent

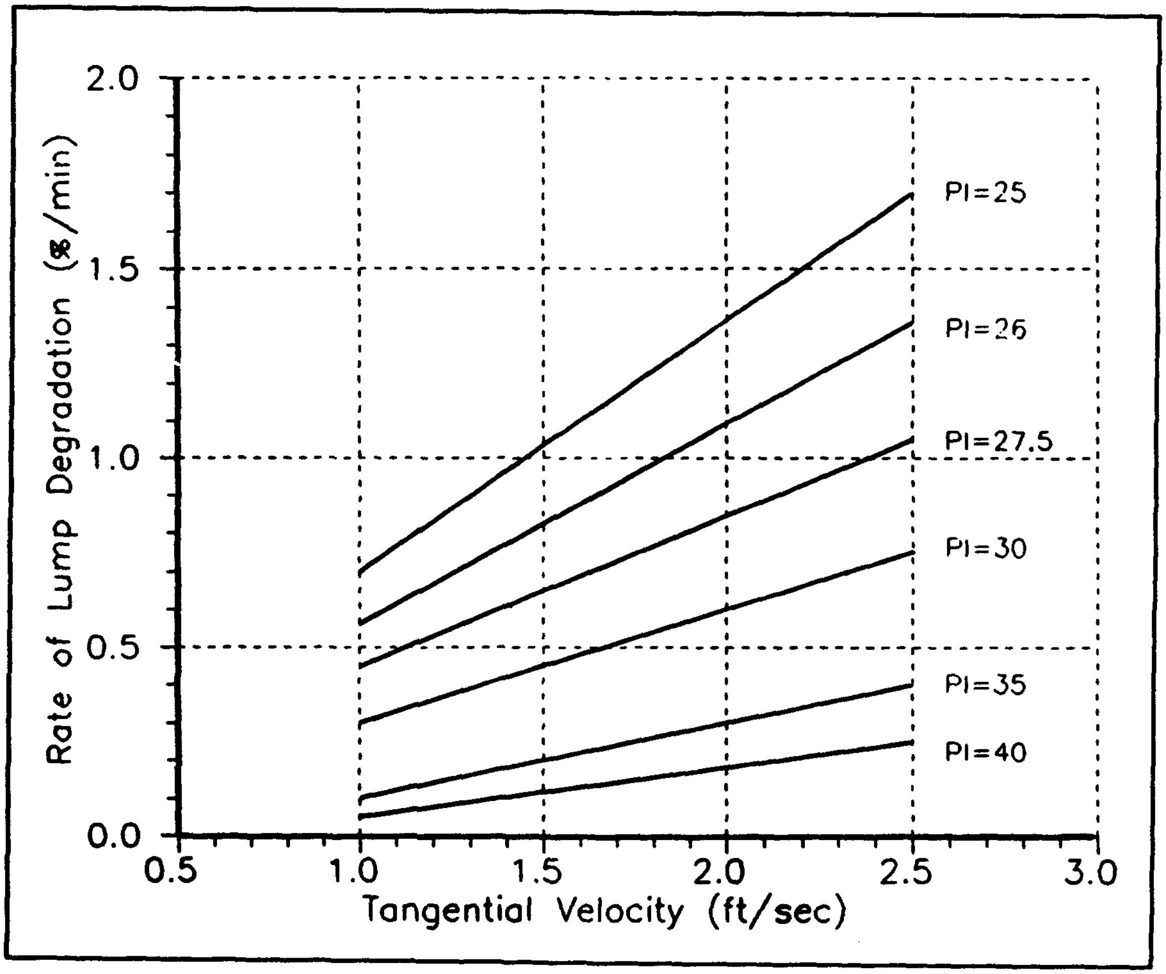


Figure 76. Rate of lump degradation versus V for spin test at Rc = 100 percent

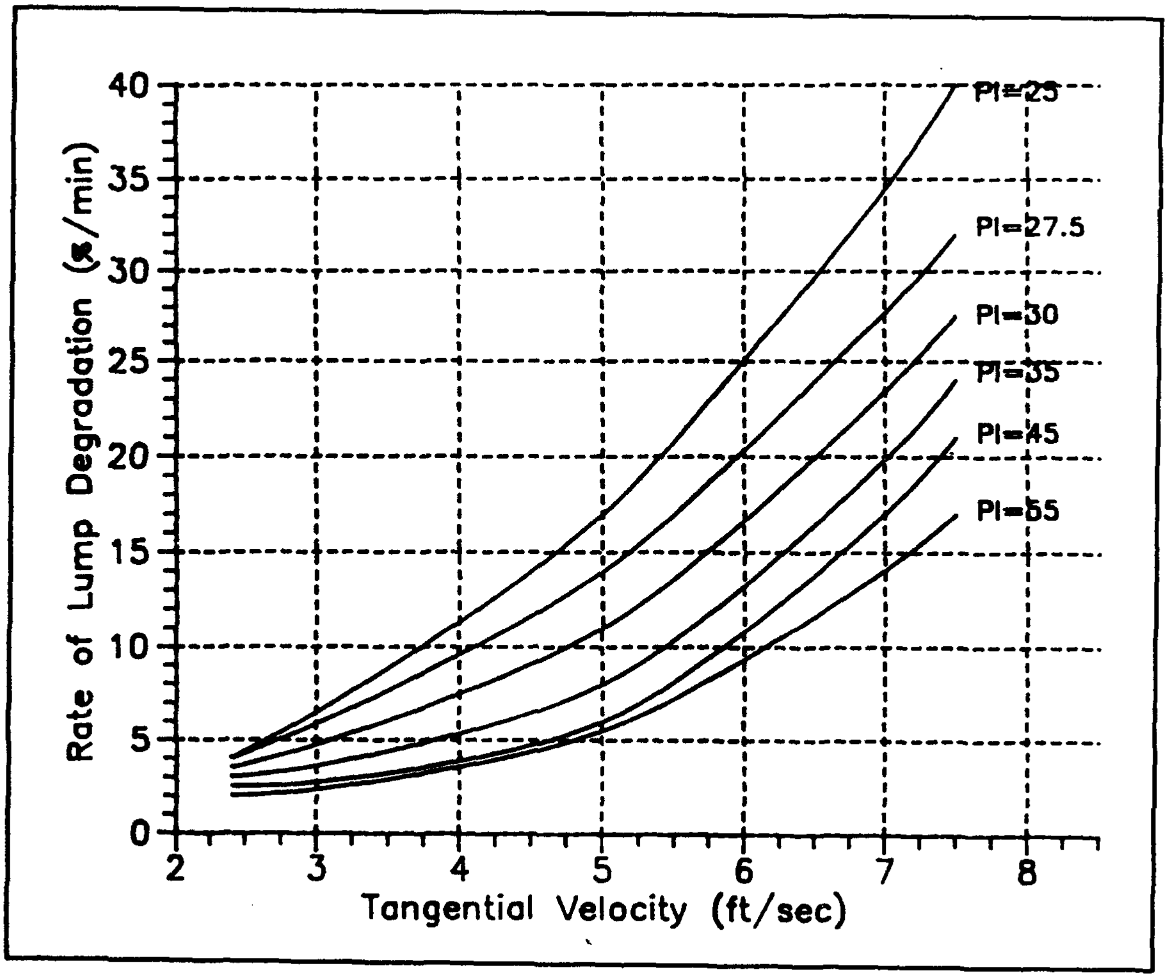


Figure 77. Rate of lump degradation versus V for rough drum test at Rc = 80 percent

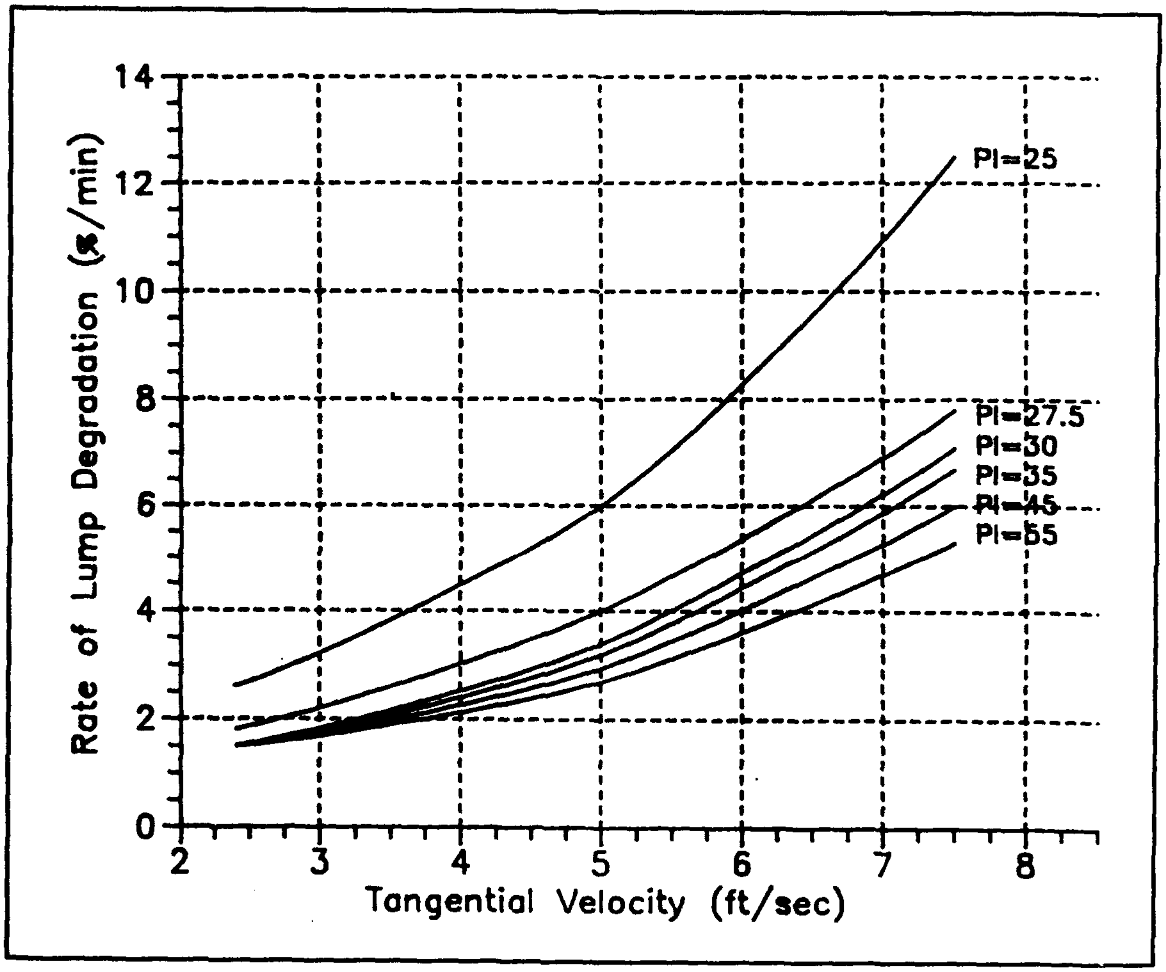


Figure 78. Rate of lump degradation versus V for rough drum test at *Rc* = 90 percent

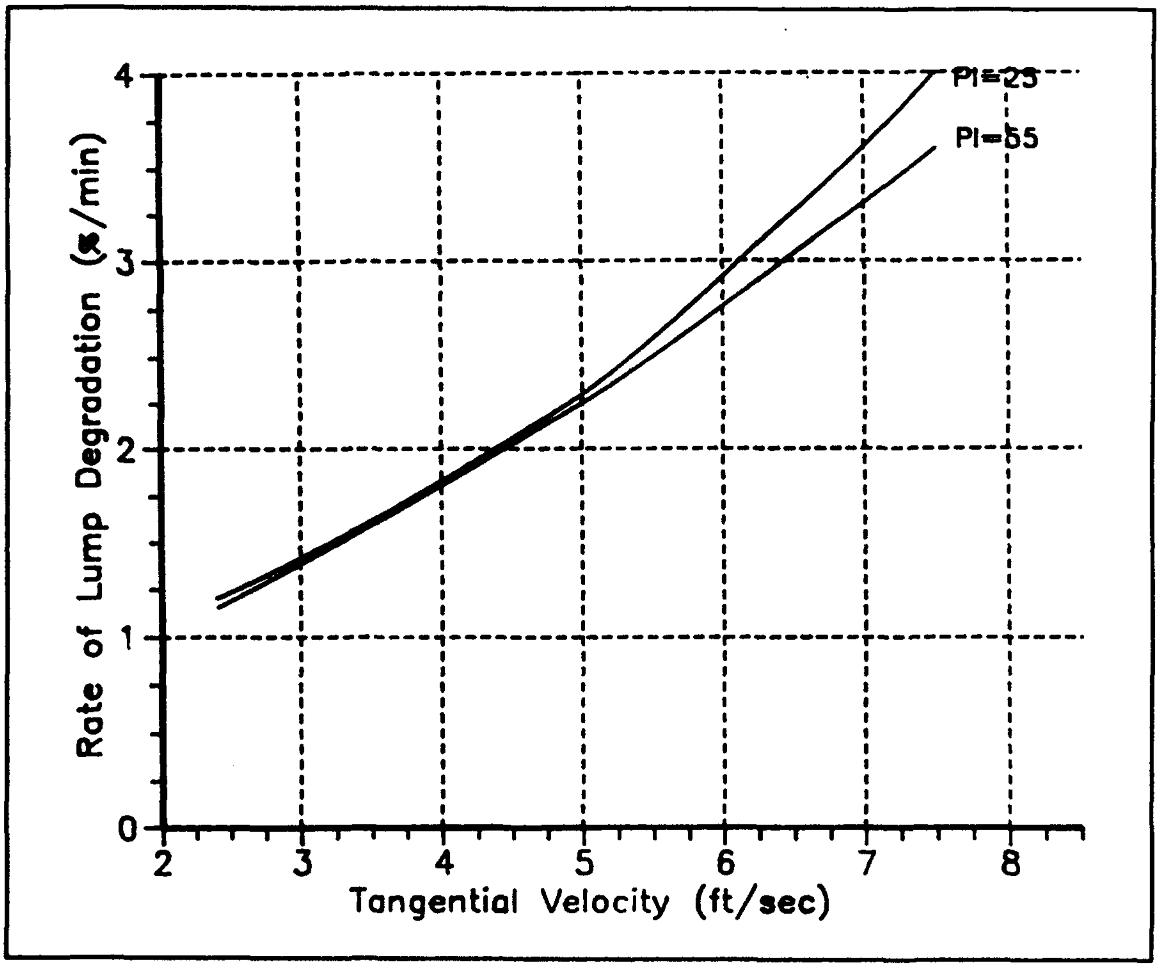


Figure 79. Rate of lump degradation versus V for rough drum test at Rc = 100 percent

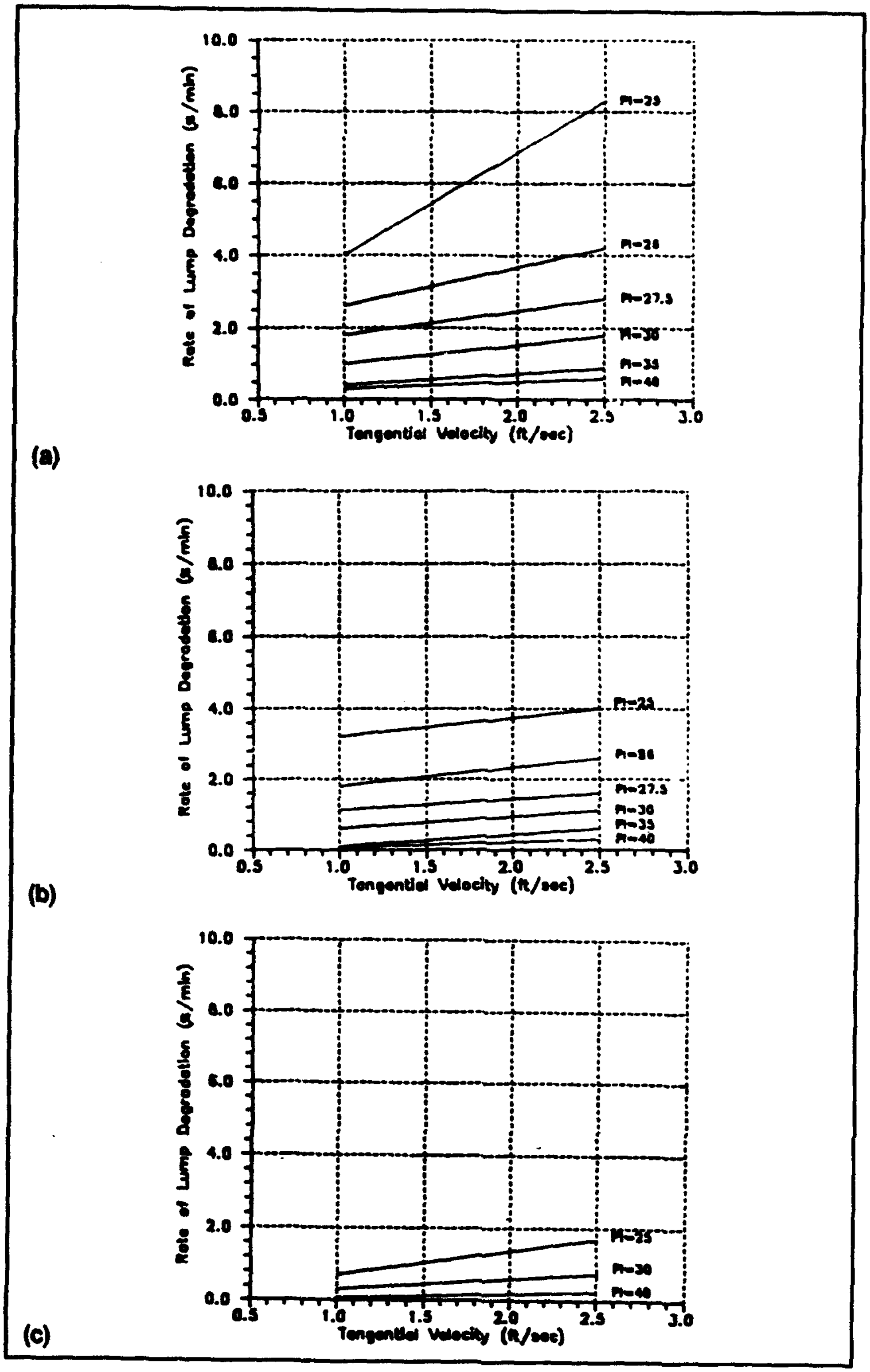


Figure 80. Comparison of rate of lump degradation versus V for spin test at various degrees of relative compaction: (a) Rc = 80 percent, (b) Rc = 90 percent, and (c) Rc = 100 percent

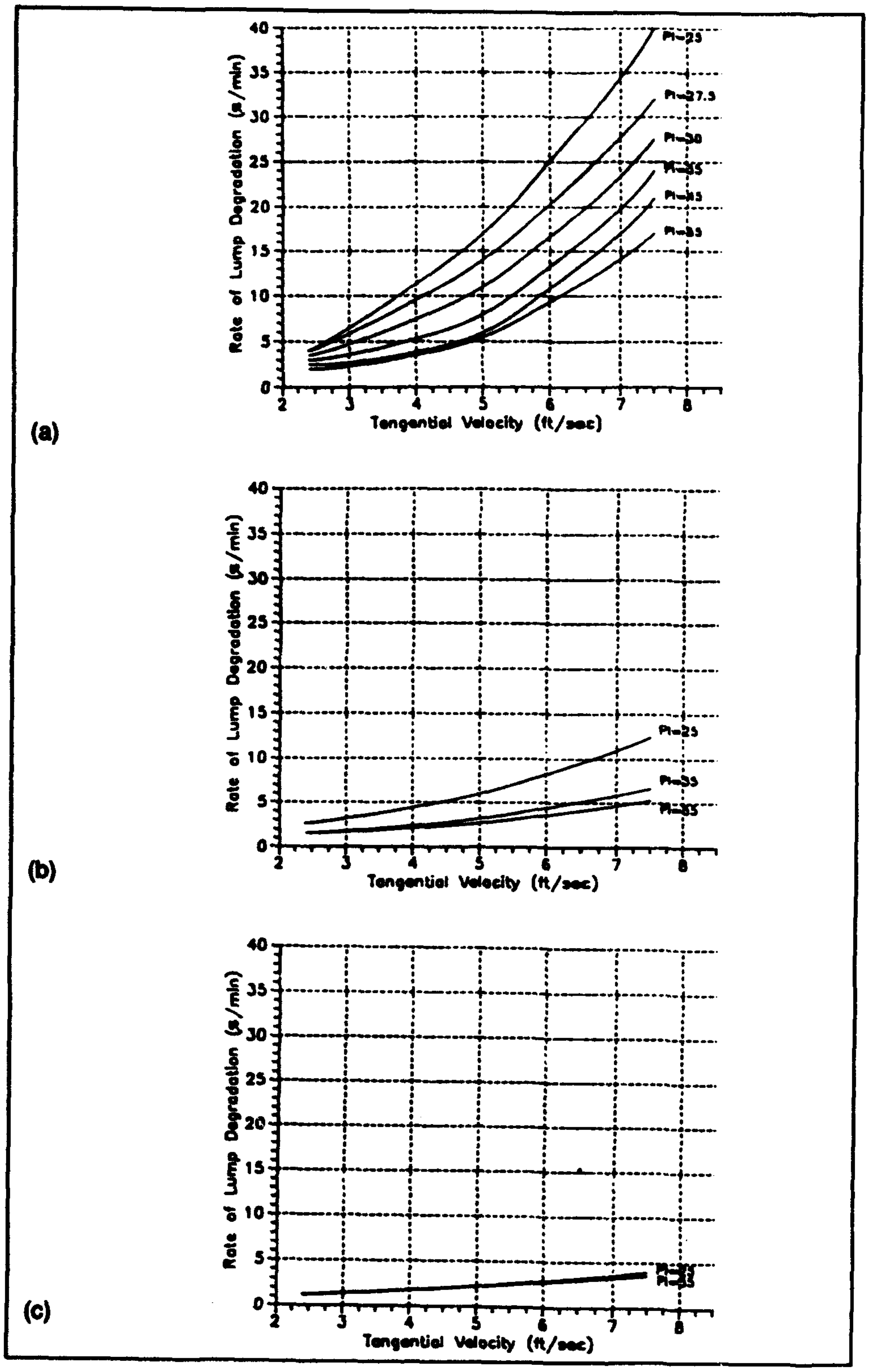


Figure 81. Comparison of rate of lump degradation versus V for rough drum test at various *Rc*: (a) *Rc* = 80 percent, (b) *Rc* = 90 percent, and (c) *Rc* = 100 percent

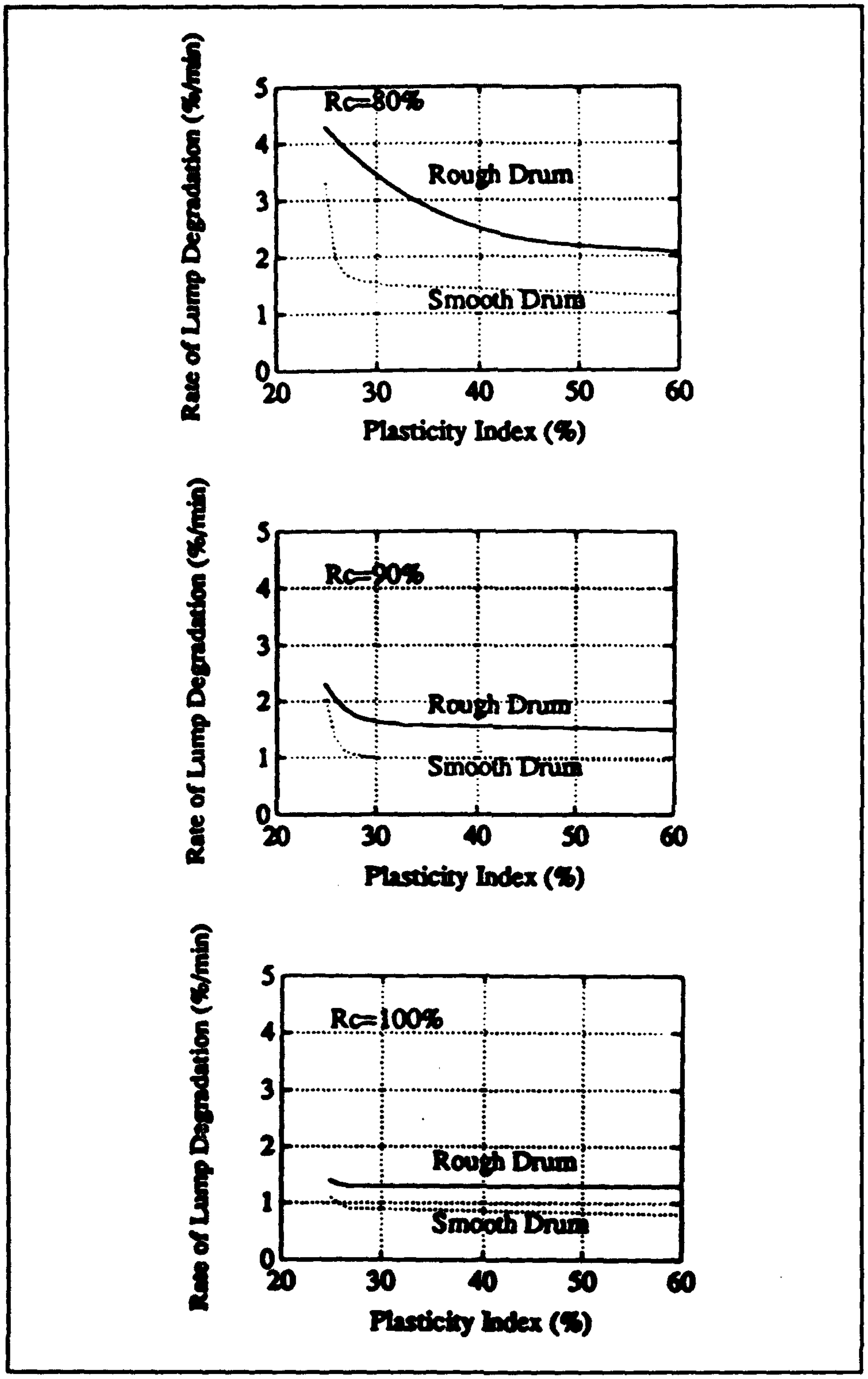


Figure 82. Comparison of rate of degradation for smooth and rough drum tests at V = 2.4 ft/sec

6 Conclusions

A method for determining degradation of clays undergoing hydraulic transport has been presented. This method is based upon experimental test results, using simulated clays, exposed to dredge-like conditions. The simulated clays were prepared under controlled conditions in the laboratory, to study the effect of plasticity (PI) and relative compaction (*Rc*) on degradation. The simulated clays were produced using different proportions of bentonite and kaolinite in mixture. This allowed clays with widely varying PI to be formed. The clays were then tested at different compaction levels as related to maximum standard Proctor. This form of expressing compaction is useful because it makes comparisons with any other soil consistent through a standardized test.

The results of the testing program clearly show that plasticity and relative compaction have significant effects on rate of degradation. For heavily compacted material (near 100 percent of maximum standard Proctor), the rate of degradation was found to be nearly zero for any plasticity index greater than 25 percent. For lightly compacted clay, the rate of degradation was found to be a function of plasticity. Rates of degradation for light to moderately compacted clays with PI between 25 percent and 35 percent are rather slow. As plasticity increases above PI = 35 percent, however, rate of degradation becomes negligible. Hence, clay balling is likely to occur when PI>35 percent. Conversely, slurrification of dredged clay lumps is likely to occur when PI<25 percent.

The degradation effects caused by hydraulic transport on the tested clays have been conveniently presented in the form of design charts. This allows predictions regarding degradation to be easily made based on simple and relevant geotechnical properties of the clay to be dredged. These design charts are presented in Figures 77 through 79. To use the charts, three properties of the soil to be dredged must be determined, and the hydraulic conditions under which it will be transported must be known. The soil properties needed are the plasticity index (PI) of the soil, the maximum standard Proctor dry density of the soil, and the field dry density of the clay, which is a measure of how compact the soil is in its natural state. Determination of these properties is a simple and relatively inexpensive process. The hydraulic transport condition needed to make degradation predictions is the relative velocity of the transport fluid to the clay lumps. This can be estimated as the difference between the pipeline discharge (e.g., cu yd of liquid per hr) minus the excavation

(production) rate (e.g., cu yd of excavated clay per hr), divided by the pipe cross-sectional area.

The results presented have important applications for the dredging industry because they can be used to predict dredged clay behavior. Further verification of the accuracy of degradation predictions is needed. The results provide, however, a rational link between the geotechnical characteristics of clays and the behavior of the material when dredged.

References

Dunlap, W. A. (1993). "European dredging overview with emphasis on geotechnical descriptors," Contract Report DRP-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Herbich, J. B. (1975). *Coastal and Deep Ocean Dredging.* Gulf Publishing Corp., Houston, TX.

Hudson, J. (1970). "Hydraulic dredging: theoretical and applied," Cornell Maritime Press, Cambridge, MD.

Leshchinsky, D. "Descriptors for granular soil," in preparation, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lord, E. R. F., and Isaac, B. A. A. (1988). "Geotechnical investigation of dredged overburden at the oil sand mine in Northern Alberta Canada," *Canadian Geotechnical Journal* (26), 132-53.

Mohr, A. W. (1980). "A practical method for estimating pipeline dredge production." *Proceedings of the Third International Symposium on Dredging Technology.* Bordeaux, France, Paper C1, 89-97.

National Research Council Marine Board. (1985). "Dredging coastal ports," National Academy Press, Washington, DC.

Richter, S. D. (1991). "Degradation of clay under hydraulic transport conditions," M.S. thesis, Department of Civil Engineering, University of Delaware.

Sargent, J. H. (1968). "Site investigations for modern dredging practice." *Proceedings of the World Dredging Congress.* WODCON II, Rotterdam, The Netherlands, 315-37.

Sorensen, A. H. (1984). "Soil analysis and dredging." *Proceedings of Dredging and Dredged Material Disposal.* ASCE Dredging '84, Clearwater Beach, Florida, 334-46.

Spigolon, J. F. (1993). "Geotechnical factors in the dredgeability of sediments: Report 1, descriptors for sediments to be dredged," Contract Report DRP-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Turner, T. M. (1984). "Fundamentals of hydraulic dredging," Cornell Maritime Press, Centreville, MD.

U.S. Army Corps of Engineers. (1990). "New Bedford harbor superfund pilot study evaluation of dredging and dredged material disposal," U.S. Army Corps of Engineers, New England Division.

______. (1972). "Soil sampling," Engineer Manual 1110-2-1907, Washington, DC.

Verbeek, P. R. H. (1984). "Soil analysis and dredging," *Terra et Aqua* (28), 11-21.

Verhoeven, F. A., Jong, A. J. de, and Lubking, P. (1988). "The essence of soil properties in today's dredging technology," Hydraulic Fill Structures, Ft. Collins, Colorado, Geotechnical Special Publication No. 21, American Society of Civil Engineers, New York.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1994

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Hydraulically Transported Clay Balls

5. FUNDING NUMBERS
DACW39-91-C-2471

6. AUTHOR(S)
Stephen D. Richter, Dov Leshchinsky

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Leshchinsky Associates
33 The Horseshoe
Covered Bridge Farms
Newark, NJ 19711

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000;
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Contract Report DRP-94-1

11. SUPPLEMENTARY NOTES
This report is available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Behavior of dredged clay lumps varies widely depending upon their geotechnical characteristics. Predicting the behavior of clay lumps in important in estimating the difficulties associated with the transporting phase of dredged materials. Existing engineering soil descriptors are not oriented towards dredging operations and therefore cannot be used for accurate behavior predictions. Usage of these predictors in practice often leads to disputes between the parties involved in the dredging project.

This work presents the empirical relationship between basic clay properties and the degradation rate of clay balls being hydraulically transported. Various clay consistencies were simulated in the laboratory using different porportions of kaolinite and bentonite in mixture. These clays were then statically compacted to different degrees of density relative to their maximum standard Proctor dry density. To simulate the hydraulic transport effects, samples were subjected to two types of tests. In the first one, clay samples were clamped and lowered underwater and were spun for different times and velocities. The remaining intact portions of the samples were then dried and wieghed to determine the effect of the relative movement of water against the clay. In the second test, clay samples were placed in a drum, partially submerged in water. The drum was rotated for different times and various velocities. Intact portions of samples were then removed from the drum, dried, and weighed to determine the effect of agitation.
(Continued)

14. SUBJECT TERMS
See reverse.

15. NUMBER OF PAGES
110

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. (Concluded).

The results of the testing program showed that plasticity and relative compaction of the soil play a significant role in the rate of degradation of clay balls. Through extensive testing, design charts have been established to estimate the rate of degradation based on these basic properties. By determining these properties of an in situ soil, one can then predict whether the dredged clay lumps will slurrify or clay balls will form. The results appear to be important to the dredging industry, as they reduce some of the uncertainty commonly associated with the planning and execution of a dredging project.

14. (Concluded).

Clay balls
Dredge descriptors
Dredge efficiency
Dredge estimating and planning
Dredged material
Dredging
Hydraulic dredging